Master Thesis, Department of Geosciences

Leaching of PFCs from soil polluted by firefighting activities

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Abstract

Per- and poly-fluorinated compounds (PFCs) are a large group of anthropogenic chemicals that holds unique surfactant properties. PFCs have been used in a wide range of domestic, commercial and industrial products, and have been released to the environment from various sources. The compounds are ubiquitous in the environment on a global scale, and have for instance been detected in arctic regions and in human serum samples from general populations. Due to PFCs chemical properties the compounds are toxic, persistent in the environment, bioaccumulating in organisms, biomagnifying in the food chain, and can be carcinogenic. Based on the adverse effects of PFCs in the environment perfluorooctosulfonic acid (PFOS), the compound that was considered of most concern, was recently prohibited in Norway (2007) and Canada (2008). PFOS was added to Annex B of the Stockholm convention on persistent organic pollutants in 2009.

Aqueous film forming foam (AFFF), a type of fire fighting agent used for extinguishing hydrocarbon fueled fires, contains PFCs. AFFF has been released to soil at airport fire fighting training stations, often through many years of fire fighting training activity. This Master thesis was initiated to obtain knowledge on the leaching behavior of PFCs from soil polluted by AFFF. Leaching of PFCs from soil is controlled by the individual compounds physicochemical properties, and the compounds chemical interaction. However, the soil characteristics also have a great influence on the leaching behavior of the compounds. The objectives were to use laboratory experiments for determining equilibrium partitioning coefficients (K_d) of PFCs between different soil types and porewater, study the influence of various soil charachteristics for sorption of PFCs, and describe the leaching of PFCs from different soil types.

Laboratory experiments were performed with soil samples from airport fire fighting training stations. Three Avinor airports were chosen where PFCs had been detected in the soil and groundwater at both older and active fire fighting training stations. Each airport has a distinct soil type which affects the transport of PFCs in the ground. In total seven different soil samples polluted by fire fighting activity were collected at these airports.

Batch experiments in triplicate where performed for the seven soil samples, using a solid to liquid ratio of 10 for 10 days to reach equilibrium. PFC compounds with short carbon chain length (< 8C) was found to have a higher relative contribution to the ΣPFCs in the aqueous phase than in the soil. Compounds of longer carbon chain (≥ 8C) was found to have a higher relative contribution to the ΣPFCs in soil than in the aqueous phase. K_d for perfluorocarboxylic acids (PFCAs) were found to increase with increasing carbon chain length. K_d for perfluorosulfonic acids (PFSAs) was found to be higher than for PFCAs of similar carbon chain length. Leaching of three PFCA compounds with short carbon chain length (< C8) was dependent on the total concentration in soil. Leaching of four PFC compounds with long carbon chain length (≥ C8) was decreasing with increasing calcium concentration in the soil.

Leaching behavior of PFCs from soil was also studied using column experiments with the three soil types from the selected airports. Column experiments in parallel were performed using undisturbed soil columns from two sites, and for one site soil columns were repacked. Fresh water was infiltrated in the soil columns operated under saturated conditions, using a solid to liquid ratio of 10. The effluent water was sampled regularly during the 35 days experimental period to determine the leaching of PFCs from the soils. The relative contribution of shorter carbon chain compounds (< C8) decreased in leachate from the columns over time. Compounds with longer carbon chain length (≥ C8) had an increasing relative contribution in leachate over time. When comparing with the batch experiment, compounds with longer carbon chain length (≥ C8) had leached out more of the total amount from soil in the columns. The PFSA compounds were also in the column experiments higher retained in soil than the acidic compounds of similar carbon chain length.

Foreword and acknowledgments

The problem concerning environmental pollution of PFCs on Avinors airports was first introduced to me by Kim Rudolph-Lund, in August 2011. During February 2012 Gijs D. Breedveld (NGI and UiO), Kim Rudolph-Lund (Sweco) and Gro D. Villanger (Avinor) agreed to be my supervisors on a Master thesis, having soil pollution of PFCs as subject. The Master thesis was funded by Avinor, and laboratory and office facilities were provided by NGI.

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I am grateful to the department of environmental engineering at NGI for their hospitality. Thank you Geir Åsli (NGI) for advises, help and assistance in the laboratory, and for following up the column experiments. Thank you Hans Peter Arp (NGI) for the comments on the behavior of PFCs, and guidance on the preferred laboratory methods when handling these substances. Oddmund Soldal, Edana Fedje, Arve Misund (COWI) and Avinor airport personnel at Bergen, Kristiansund and Kristiansand airports are acknowledged their help, advises and practical contributions during field work. The contributions of the University of Oslo, including the help with TOC and TC analyzes of Mufak Naoroz are highly valued and gratefully acknowledged.

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1. Introduction

1.1 Per- and poly-fluorinated compounds (PFCs)

Per- and poly-fluorinated compounds (PFCs) are a broad group of anthropogenic chemicals used in many different industrial and consumer products (de Solla et al., 2012). PFCs have become of prominent concern during the past decade because they are widespread in the environment, bioaccumulate in organisms and are persistent to environmental degradation (Awad et al., 2011). The compounds have a common characteristic structure with an organic functional group (R) connected to one end of a perfluorinated alkyl tail ($F(CF_2)_x$). This gives a general formula of this group $F(CF_2)_xR$ as shown in ***Figure 1***, from which it is clear that in the alkyl chain all hydrogens are replaced with fluorines. Depending on the structure of the organic functional group, PFCs can be divided into two important subsets; perfluoroalkyl compounds and fluorotelomers. The first subset of compounds has no C-H bonds in the R-group, while the fluorotelomers have an even numbered alkyl chain in the organic functional group as shown in ***Figure 1*** (Klif, 2010).

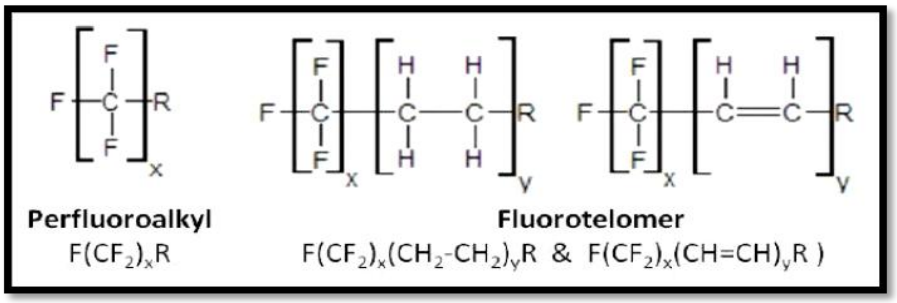


Figure 1: General chemical structure of perfluoroalkyls and fluorotelomers (Klif, 2010).

Perfluoroalkyl compounds can be divided in two groups that have been most used industrially: perfluorosulfonic acids (PFSAs) and perfluorocarboxylic acids (PFCAs). PFSAs and PFCAs are strong acids as their proton is easily lost and they become ions. The octyl forms, perfluorooctosulfonic acid (PFOS) and perfluorooctanoic acid (PFOA), are the two molecules that have gained the main attention and concern due to their elevated concentrations in the environment. General molecular structures of these compound classes are shown in ***Figure 2***, together with the structure of the octyl forms: PFOS and PFOA (Klif, 2010). For substances

that contain one or several parts of the PFOS molecular structure (the PFOS moiety is defined as $C_8F_{17}SO_2$) and potentially degrade to PFOS in the environment, the term PFOS-related substances is used (Brooke et al., 2004; Klif, 2008c). Another commonly used term for these substances is PFOS derivatives (Environment Agency, 2012).

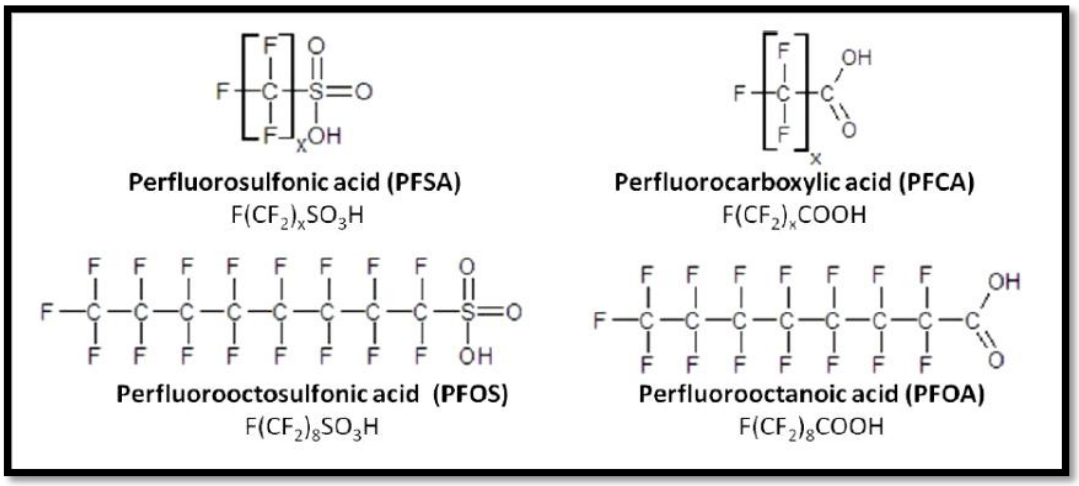


Figure 2: The two main groups of PFCs that have been most widely used industrially, and the two forms that have been of greatest concern for the environment (Klif, 2010).

Compared to similar hydrocarbons, PFCs have higher thermal stability, acid strength, surface activity, and greater ability to lower the surface tension in aqueous solutions. The perfluorinated alkyl tail of PFCs is also both water and oil repellent (Moody et al., 2000b). These physio-chemical properties, together with the ability to facilitate the mixing of oil and water have made these compounds very useful for a wide variety of products (Klif, 2010). PFCs have been used in products such as aqueous fire fighting foam, surfactants, fluorinated polymers, cosmetics, greases, paints, polishes, herbicides, insecticides, carpeting and waxes (Moody et al., 2000a; Moody et al., 2000b; Murakami et al., 2009; de Solla et al., 2012). Salts of PFOS and compounds that may degrade to PFOS have been used in shampoo and anti-static agents, as coating material on photographs and textile products, and in wafer photolithograpy (Moody et al., 2003; Tang et al., 2006). PFCs have been, and are even today, being used extensively in paper coating approved for food contact (Trier et al., 2011).

1.2 PFCs in the environment

Despite the fact that perfluoroalkyls are not found naturally in the environment, they have been detected in soil, surface and groundwater, sediment, air and biota across the globe (Kallenborn et al., 2004; Betts, 2007; Klif, 2008b; Butt et al., 2010; Awad et al., 2011; Karrman et al., 2011; de Solla et al., 2012), as well as in human serum samples collected from general populations (Karrman et al., 2006; Haug et al., 2009; Lindh et al., 2012). For instance the four compounds PFOA, PFOS, perfluorohexane sulfonate (PFHxS) and perfluorononanic acid (PFNA) have been detected in general populations in Poland, Ukraine, Greenlandic Inuits, and the U.S. (Betts, 2007; ATSDR, 2009; Lindh et al., 2012). Considerable amounts of PFCs are released in the environment at both point sources and diffuse sources. The use of aqueous film forming foam (AFFF) during fire fighting training is an example of a point source (Gellrich et al., 2012a). Diffuse sources are from the use and disposal of consumer products such as PFC treated carpets, and paper (Paul et al., 2008), as well as urban runoff (Murakami et al., 2009) and air pollution in cities (Muller et al., 2012). Possible pathways of PFCs released in the environment are shown in ***Figure 3***.

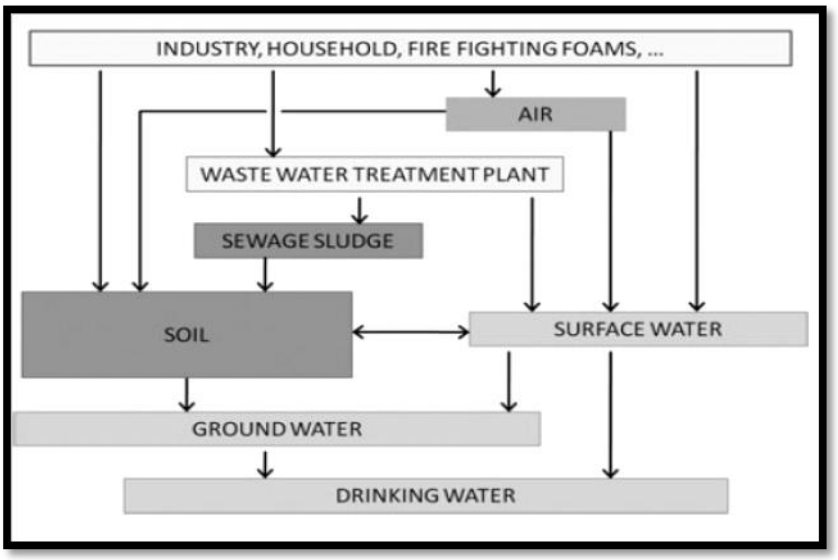


Figure 3: Pathways of PFCs emitted in the environment (Gellrich et al., 2012).

PFCs from different sources can accumulate in sewage sludge at waste water treatment plants and later be applied to fields as fertilizer. Even though some countries regulate the PFOS and PFOA concentrations in the sewage sludge, other PFC compounds can be found in the sludge (Gellrich et al., 2012a). In the outlet water from three sampled municipal waste water treatment plants in Norway, the compounds perfluorobutane sulfonate (PFBS) (1.0-2.6 ng/l), PFHxS (1.8-2.3 ng/l), perfluorohexanoic acid (PFHxA) (14-15 ng/l), PFOA (20-22.5 ng/l), and PFNA (1.25-3.55 ng/l) were found. Most dominant was, however, PFOS with a concentration range of 6.89-18.3 ng/l (Kallenborn et al., 2004). Marine sediments from harbors near cities might give an indication of the PFC content in urban runoff. In the Oslo harbor, Norway, investigations of sediments showed low concentrations of PFCs. In both surface samples and core samples of the sediments only three compounds were detected; PFOS (0.10-0.38 µg/kg), perfluorodekane sulfonate (PFDS) (0.02-0.66 µg/kg) and perfluorooctane sulfonamide (PFOSA) (0.04-0.12 µg/kg) (Klif, 2008a).

Perfluoroalkyls are also found in arctic areas, indicating ongoing long-range transport (Butt et al., 2010). One proposed mechanism is direct transport by oceanic currents, supported by measurements of perfluoroalkyl substances in ocean waters and elevated levels in coastal areas with industry. Atmospheric transport in the vapor phase or on marine aerosols are other proposed mechanisms. Fluorotelomer alcohols (FTOHs), sulfonamidoethanols and perfluoroalkyl sulfonamides have been detected in arctic and urban air samples (ATSDR, 2009; Muller et al., 2012).

Perfluoroalkyl compounds that have entered the environment, especially PFOS, have been found to bioaccumulate in protein containing tissue of wildlife. The highest concentrations tend to be in blood, liver and kidneys (de Solla et al., 2012). This is in contrast to other known persistent organic pollutants, for example PCB and PBDE, which commonly accumulate in fat tissue (Karrman et al., 2006; Niva, 2007; de Solla et al., 2012). Biomagnification of the compounds in food webs are indicated as polar bears (*Ursus maritimus*) and other top-level predators have the highest measured concentrations in animals. The persistence of PFCs in the body is affected by the chain-length, and longer carbon chains give higher persistence (Betts, 2007; ATSDR, 2009). The eight carbon chain compounds PFOS and PFOA can lead to cancer by acting as an inhibitor of communication between cells (Klif, 2010), and PFOS has been

linked to bladder and liver cancer (OECD, 2002). Potential pathways of human exposure to PFCs are thought to be through air, water, food and dust in houses (Karrman et al., 2006).

1.3 Regulations of PFCs

PFOS and PFOA have received the most focus in toxicological studies of PFCs (Klif, 2010), and PFOS is at the time most strongly regulated by many countries (Vierke et al., 2012). The U.S. Company 3M was the principal global manufacturer of PFOS (3M, 2003; ATSDR, 2009), until the company in 2000 announced that they would phase out PFOA, PFOS and the PFOS –related products in their production (Moody et al., 2000b; Brooke et al., 2004; ATSDR, 2009; 3M, 2012). This was after researchers had discovered that PFOS was widespread in wildlife and detected in humans at low levels. The 3M phase-out of PFOS was completed in 2002, and their use of PFOA in production processes ceased in 2008 (3M, 2012). Production of the compounds is, however, continuing in unknown quantities by Southeast Asian companies (Paul et al., 2008; Karrman et al., 2011). Norway prohibited PFOS and PFOS-related components for use in fire fighting agents, textiles, and impregnation in April 2007 (Klif, 2008c). Canada banned the substance for manufacture, import, use and sale in 2008 (Canada Gazette, 2008). In 2009, the European Union and its member states agreed to add PFOS-related compounds to Annex B of the United nations' Stockholm convention on persistent organic pollutants (POPs). This means that restrictions apply for the production and use of these compounds. An example is the concentration limits given for preparations (10 mg/kg) and products (1 $\mu g/m^2$ for textiles). As there are no alternatives at the time, many important uses are exempted from the restrictions of Annex B. The restriction of PFOS related compounds in the production of AFFF was enforced immediately, while the use of existing stocks was allowed until June 2011 (European Union, 2010). Vierke et al. (2012) highlights the absence of measures regulating PFOA, and suggest the compound to be listed as a substance of very high concern (SVHC) under REACH. REACH is the European community regulation for safe use of chemicals (European Commision, 2012).

1.4 Objectives

To evaluate the potential for spreading of PFCs with groundwater, more data on leaching behavior of these compounds from different soil types is needed. The three objectives of this Master thesis were to: (1) find the partitioning equilibrium coefficients (Kd) of selected PFCs between porewater and different types of soil by using batch experiments, (2) study the influence of various soil charachteristics for sorption of selected PFCs by using batch experiments, and (3) describe the leaching of selected PFCs from different soil types by using undisturbed soil column leaching experiments. Soil samples for laboratory experiments were collected at three Avinor airports. Investigations at these airports had previously revealed PFCs in samples of soil, water and biota at both older and active fire fighting training stations. The dominating compound detected in the samples was PFOS, despite that Avinor stopped the usage of AFFF with PFOS as the dominant and active PFC ingredient at their airports by the end of 2001 (Avinor, 2012d). The results from this Master thesis will be used for evaluating groundwater transport and spreading of PFCs at Avinors airports and as a basis for evaluating the environmental risk.

2. Background

2.1 Avinors environmental project

Many different chemicals are used as a necessary part of the operation and maintenance of airports, with a potential to pollute the surrounding environment. Accidental jet fuel or fuel oil spills, use and spill of deicing chemicals for airplanes and runways, and the use of aqueous film forming foam (AFFF) as an extinguisher for fuel-based fires in aircrafts and at fire fighting training sites, are all examples of this. In Norway, Avinor AS owns, operates and maintains a nationwide network of over 40 civilian airports (Avinor, 2012a). As a part of Avinors responsibility to sustain the quality of the surrounding environment at the airports, the environmental status and pollution risks at all their airport facilities were mapped in the period from 2008 to 2010. The investigations revealed various environmental risks that needed further follow-up. To ensure follow-up of the detected risks, Avinor`s environmental project

("Miljøprosjektet") was established. The project is divided into nine parts (or sub-projects), covering physical/technical and operative measures to reduce the risks of pollution. The technical investigations to map pollution that poses an environmental risk should be complete during the fall of 2012. The practical accomplishment of the planned remedial measures and completion of the environmental project proceeds in the period from 2013 to 2015 (Avinor, 2010; Avinor, 2011e).

In 2011, as part of the described environmental project, the mapping of PFOS and PFOA concentrations in mainly ground and groundwater around airport fire fighting training stations was performed. The environmental pollution of these two compounds was found to be extensive; especially PFOS was detected in soil, groundwater, receiving waters and biota at most airports. This led to increased focus also on other PFCs, that from analyzes of the samples were found to be present. PFCs have been released to the environment at Avinor airports from the use of AFFF during mandatory training of airport personnel. Today Avinor has 14 airport fire training sites in active use for this purpose (Avinor, 2010). Traditionally there were fire fighting training sites in connection to each airport. Increasing demand of pollution management at these sites has lead to centralization of the activity on specialized training platforms to control the waste water and minimize environmental impact (Avinor, 2012d), however the abandoned training sites still pose an additional environmental challenge. From the use of AFFF at Avinors airport fire fighting training sites in the period from 1998 to 2011, an estimated 3400 kg of PFCs have been released each year. Spreading of PFOS with groundwater is evident from findings of high concentrations in groundwater at sites where concentrations in soils are low (Øvstedal, 2012b). In the aftermath of the revealed PFC pollution, a growing focus on the transport and spreading of PFOS and PFOA evolved. This led to the comprehensive goal of clarifying the extent of spreading of these compounds, as well as the most important spreading mechanisms (Avinor, 2012d).

In Norway, the guidelines for management and remediation of perfluorinated substances are yet to be decided by the Climate and Pollution Agency (Klif) (Avinor, 2010). The limit for soil to be characterized as "clean soil" applies only to PFOS, and is set to concentrations < 100 µg/kg. Limits for the content of PFOS in water are not yet determined, the proposed values for the European Union's water framework directive with regard to human health are

0.65 ng/l in freshwater, and 0.13 ng/l in marine water. The Norwegian Institute of Public Health has recommended a limit on the content of PFOS in drinking water of 300 ng/l, based on German limits (Øvstedal, 2012a). There is an ongoing discussion about where the limits shall be applied. Avinor initiated a workshop to discuss criteria for acceptable risk, and methods for remediation of areas polluted by PFOS in 2012 (Øvstedal, 2012b). It turns out to be difficult to set this acceptance criterion due to the present lack of knowledge. It was agreed that more time is needed for research on the risk posed by the presence of PFOS in the environment. In the mean time, action has to be taken in heavily polluted areas at Avinor`s airports. During the work of this thesis, there was an increasing awareness that releases of other PFCs also pose a danger to the environment. Sources, travel routes and biological targets of these PFCs also need to be studied. After Avinor stopped using AFFF containing PFOS in 2001, the AFFF used for firefighting training still contained PFCs with properties similar to PFOS. The use of for example 6:2 fluorotelomer sulfonate in AFFF, is not restricted since the regulation enforced through Annex B of the Stockholm convention only apply for PFOS related compounds (Environment Agency, 2012). In the AFFF Avinor used from 2001 to 2012, PFOS was mainly replaced by fluorotelomer compounds (Øvstedal, 2012a). Avinor is currently carrying out their most important measure against further environmental pollution of PFCs. They are starting to use of a new fire fighting foam that is free of fluorinated compounds (Avinor, 2012b).

2.2 Production of PFCs

PFCs are synthetically manufactured either by the electrochemical fluorination process (ECF), or a process known as telomerization (Moody et al., 2000b; ATSDR, 2009). Of these two processes, ECF has low to moderate yields of PFCs and many side products; still it is the economically attractive process (Moody et al., 2000b). The bulk production of PFC by the 3M Company (the main global PFC manufacturer) from 1949 to 2002 used the ECF process. This crude production process resulted in both odd and even carbon chain lengths and both branched and linear molecules (Paul et al., 2008; Karrman et al., 2011). The telomerization process produces only even numbered carbon chain lengths and linear carbon chains. If

structural isomers are separated in analytical ways, the combination of odd and even numbered carbon chain lengths in the environment can be linked to producers using the ECF process (Moody et al., 2000b; Karrman et al., 2011). The 3M and other companies mainly produced perfluorooctane sulfonyl fluoride (POSF; $C_8F_{17}SO_2F$) by the ECF process, which was further used as a starting chemical for production of a broad variety of fluorocarbons, including PFOS (Kallenborn et al., 2004; Paul et al., 2008). Paul et al. (2008) estimated the total global POSF production in the time period from 1970 to 2002 to be 96,000 tons. Around 75,000 tons of this production was by the 3M company, and 10,000 tons of the total global POSF production was used in AFFFs. From 1966 to 1990 the total global production increased from around 500 tons/year to 4,650 tons/year, and reached a stable production level for a ten year period, until a sudden drop as 3M started phasing out its production in 2000. Concerning releases to the environment, the total global release of POSF to air and water in the time period from 1970 to 2012 has been estimated to be 45,250 tons (Paul et al., 2008). As a replacement for PFOS and PFOA, FTOHs and other PFCA and PFSA compounds have been introduced. The 3M Company has shifted its production towards the shorter chained PFCs as they have shorter half-life in the human body; one of them is PFBS (Betts, 2007). PFBS is, for example, used as a substitute for PFOS in paint and impregnation products (Niva, 2007). Telomerization has since 2002 become the more common production process for PFCs (Mabury, 2009; Vierke et al., 2012), and the global yearly production of FTOHs nearly doubled in the time period from 2002 to 2004. In 2004, the global production was estimated to 11,000-14,000 tons/year (Dinglasan-Panlilio et al., 2006).

2.3 Conversion of PFCs

Compounds in the perfluoroalkyl groups perfluorosulfonic acids (PFSAs) and perfluorocarboxylic acids (PFCAs) can be regarded as end products of environmental transformations. Environmental degradation of compounds in these groups is not known to happen, although it is likely that it occurs to an immeasurable extent (Klif, 2010). This is in contrast to compounds in the PFC groups fluorotelomer alcohols (FTOHs) and polyfluorinated sulfonamides (FSAs), that are capable of conversion into compounds of the

PFCA and PFSA groups (Martin et al., 2005; Dinglasan-Panlilio et al., 2006; Stock et al., 2007; Arakaki et al., 2010; Muller et al., 2012). For instance, Ellis et al. (2004) observed the production of a variety of PFCA compounds from the oxidation of FTOHs in air. The compound 8:2 FTOH has also been found to metabolize into PFOA in rats (Martin et al., 2005; Dinglasan-Panlilio et al., 2006). Conversion N-Me-FOSE and 8:2 FTOH to PFOS and PFOA, respectively, by intermediate steps are illustrated in ***Figure 4*** (Mabury, 2009).

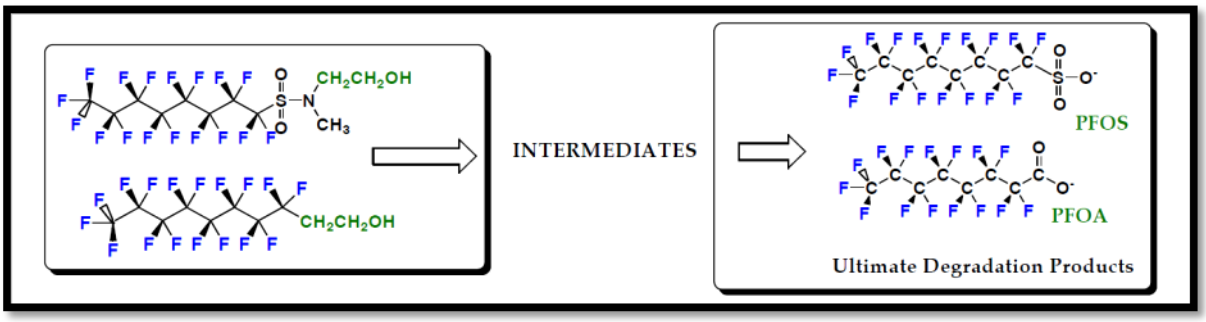


Figure 4: Compounds in the groups FSAs and FTOHs can convert of to compounds in the groups PFSA and PFCA. The figure shows that N-Me-FOSE and 8:2 FTOH can convert to PFOS and PFOA by intermediate steps (Mabury, 2009).

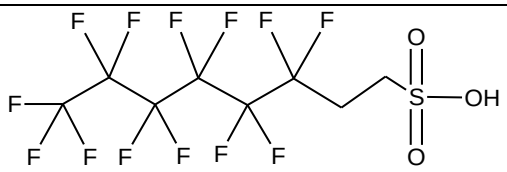
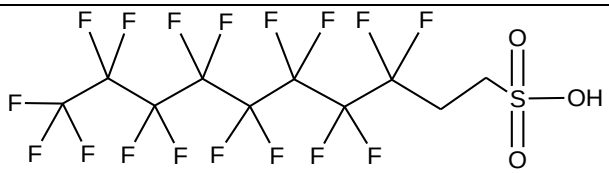
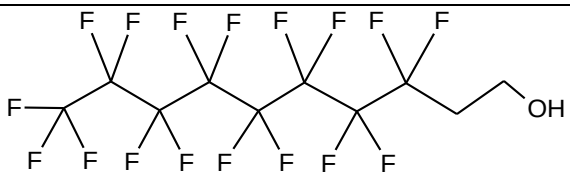
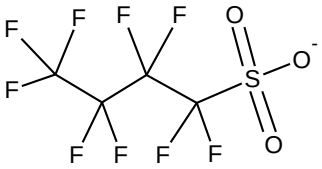
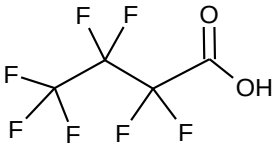
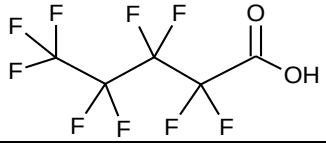
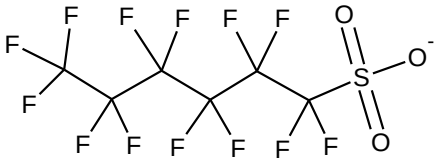
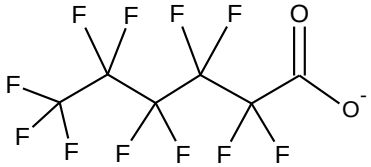
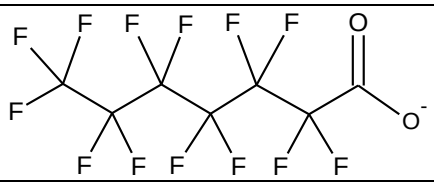
Compounds that can be transformed by various processes, like biodegradation or photo oxidation, to produce other compounds are termed precursor compounds. FTOHs and FSAs are used in the synthesis of other PFCs, and include volatile precursor compounds that often occur as residuals in fluorinated materials. As the residuals are volatile, they are easily released to the environment from materials like textiles and carpets (Dinglasan-Panlilio et al., 2006; Myers et al., 2010; OECD, 2012). Dinglasan-Panlilio et al. (2006) suggested the release and degradation of these residuals to be a significant source of PFCA in the environment. Atmospheric transport of volatile precursors that later degrade to stabile PFCs, explains the spreading of non-volatile PFCs to regions far from pollution sources (Butt et al., 2010). Being sources of the more persistent PFCs, precursor substances indirectly increases the environmental levels of more persistent PFCs; hence they pose an environmental risk (Niva, 2007). Brooke et al. (2004) specifies as many as 96 precursor substances that can degrade to

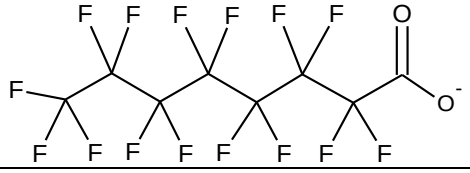
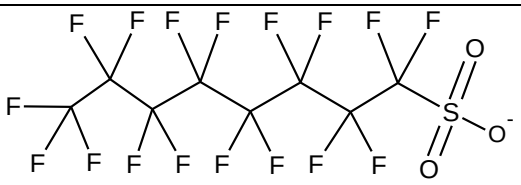
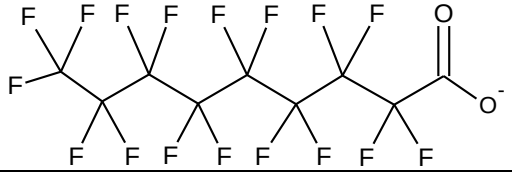
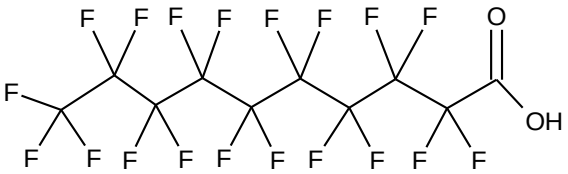
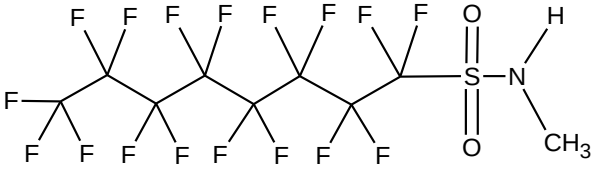
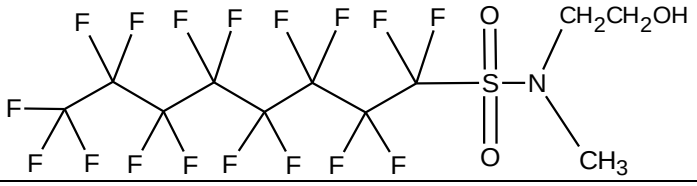
PFOS. These substances can be divided into three main groups, the first group is salts of PFOS, and the second group is individual substances that are made from perfluorooctane sulphonyl fluoride (POSF), the third group is polymeric materials named PFOS-polymers (Brooke et al., 2004). To eventually discontinue the release of PFOS and PFOA in the environment, the release of precursors must be considered. It is important that compounds used as replacements for PFOS and PFOA are neither precursors of PFOS, PFOA or other persistent PFSAs and PFCAs.

2.4 Chemical structure

There are several hundreds of different compounds included in the PFCs, and several ways of grouping them exist. Commonly the compound classes are named after their organic functional group. As previously explained, PFCs can be divided into the two important subsets perfluoroalkyls and fluorotelomers, produced by the ECF and telomerization processes respectively. It has already been mentioned that the compound classes PFCA and PFSA are included in the perfluoroalkyl subset, and that they are strong acids that lose their proton easily. Based on the ability to lose their proton, PFCs can be divided into volatile and ionic compounds. Volatile compound classes are for example FTOHs, perfluoroalkyl sulfonamides and perfluoroalkyl sulfonamidoethanols. Examples of ionic compound classes would be fluorotelomer sulfonates (FTS), PFCA and PFSA (Klif, 2009). ***Table 1*** shows acronyms, compound names and structures of compounds within the above mentioned classes of ionic and volatile compounds (Kallenborn et al., 2004; Klif, 2008b; Arakaki et al., 2010). Another way of grouping the PFCs would be into four main groups; sulfonates, alcohols, acids and sulfonamides (Kallenborn, 2012). Sulfonates are found both within the perfluoroalkyl subset and the fluorotelomer subset, represented by the classes PFSA (ionic in the environment) and FTS. Alcohols are, for example, the FTOH compound class, and an example of acids is the PFCA compound class.

Table 1: Acronyms, compound names and compound structures of PFC compounds representing the groups sulfonates, alcohols, acids and sulfonamides (Kallenborn et al., 2004; Klif, 2008b; Arakaki et al., 2010).

Acronym	Compound name	Compound structure
6:2 FTS	6:2 Fluorotelomer sulfonate	
8:2 FTS	8:2 Fluorotelomer sulfonate	
8:2 FTOH	8:2 Fluorotelomer alcohol	
PFBS	Perfluorobutane sulfonate	
PFBA	Perfluorobutanoic acid	
PFPeA	Perfluoropentanoic acid	
PFHxS	Perfluorohexane sulfonate	
PFHxA	Perfluorohexanoic acid	
PFHpA	Perfluoroheptanoic acid	

PFOA	Perfluorooctanoic acid	
PFOS	Perfluorooctane sulfonate	
PFNA	Perfluorononanoic acid	
PFDA	Perfluorodecanoic acid	
N-Me-FOSA	N-Methyl-heptadecafluorooctane sulphonamide	
N-Me-FOSE	N-Methyl-heptadecafluorooctane sulphonamidoethanol	

2.5 Chemical properties

The molecular structures of PFC compounds, as shown for some of the compounds in table 1, indicate their unique properties. The carbon – fluorine bond is a highly polarized bond, and the strongest covalent bond known. The strength of this bond is given by overlapping of fluorine 2s and 2p orbitals and corresponding orbitals of carbon, together with fluorine electronegativity (Kissa, 1994; as sited in Moody and Field, 2000). The fluorine atoms are shielding the chain of carbons from being torn apart by other substances or the surrounding environment, and degradation processes in the environment are generally not strong enough to break this particular bond. For instance the perfluoroalkyl compounds resist degradation

processes like biological degradation, photooxidation, direct photolysis and hydrolysis (ATSDR, 2009). The electron withdrawing effect of fluorine gives PFC compounds their high acid strength (Moody et al., 2000b), and hence they have low acid dissociation constants. Goss (2008) estimated acidity constant (pKa) values for 21 PFCAs to be in the range -0.1 to 4.2. The pKa value for PFOA has been an issue of discussion in the literature (Goss et al., 2009), and various pKa values has been estimated within the range -0.5 to 3.8 (Prevedouros et al., 2006; Burns et al., 2008; Goss, 2008). For PFOS a pKa value of -3.27 has been stated (Brooke et al., 2004; Campbell et al., 2009).

The perfluoralkyl tail is oleophobic, meaning that it repels oil (Moody et al., 2000b). In addition this tail is one of the most hydrophobic parts possible in a molecule (Klif, 2010). The unique surfactant properties of PFCs are a result of the hydrophobic and oleophobic combination (Kissa, 2001; as sited in ATSDR, 2009). Opposed to the hydrophobic perfluoroalkyl tail that strives to stay outside water, the anionic or acidic functional group of the compounds is among the most hydrophilic functional groups known. Having one hydrophilic end striving to get into water, and one hydrophobic end, PFCAs and PFSAs often exist in water surfaces (Klif, 2010). Transport in the water phase is likely to be important resulting from this preferred residence in water surfaces (Arp et al., 2009). Arp et al. (2009) suggested PFCAs to adsorb substantially to atmospheric water droplets. The importance of transport in the water phase is supported by measurements of PFCs in freshwater and ocean waters and (Prevedouros et al., 2006; Paul et al., 2008) and by the water solubility of PFCs. The Norwegian Climate and Pollution Agency reports an aqueous water solubility of 570 mg/L for PFOS, although they point out that there is a general lack of data concerning physicochemical properties of PFCs, and that data given in the report are only to be used as estimates (Klif, 2007). For fluorotelomer alcohols (FTOHs), PFSAs, and PFCAs the water solubility and volatility increases with decreasing carbon chain length. It has been reported a water solubility of 12-17 mg/l for 6:2 FTOH (C8) and 0.14 mg/l for 8:2 FTOH (C10). For the PFCA compounds PFHpA (C7) and perfluoroundecanoic acid (PFUA) (C9) a solubility of 118 mg/l and 92.3 mg/l has been reported respectively (Niva, 2007).

With their hydrophobic tail and hydrophilic functional group, single surfactant molecules (monomers) can form micelles when dissolved in water. Formation of micelles is a reversible

process that is dependent on temperature, and happens at concentrations above the critical micelle concentration (CMC). Micelles are aggregates of surfactant molecules where the water contact of the hydrophobic tails is minimized. The tails are gathered in the centre of the formation, and surrounded by the hydrophilic functional groups (head groups) of the molecules (Liu et al., 1996). A micelle consisting of surfactant molecules is illustrated in ***Figure 5***. For PFCs in aqueous solutions, the CMCs are lower relative to hydrocarbon analogues (meaning that PFCs forms micelles at lower concentrations) (Moody et al., 2000b). Perfluorooctanoate anion (PFO) is the conjugate base of PFOA, and a critical micelle concentration of 3.7 x 10^3 mg/l at a temperature over 20 °C was reported for the PFO anion (Prevedouros et al., 2006).

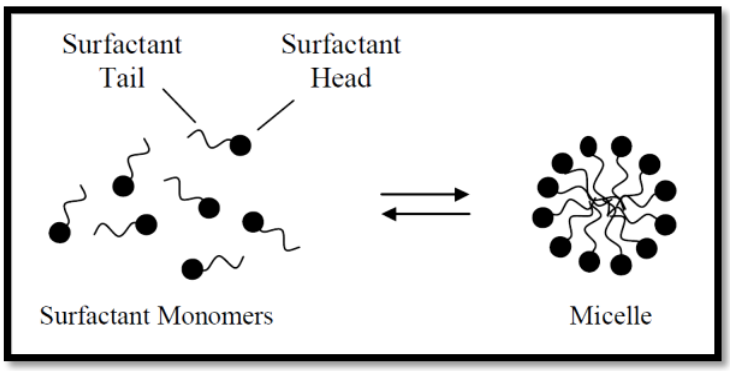


Figure 5: Illustration of the formation of a micelle in water. Above the critical micelle concentration the surfactant monomers (single molecules) assemble to form aggregates. The hydrophobic surfactant tails are shielded from the water, and the hydrophilic surfactant heads are in contact with the water (Liu et al., 1996).

Being strong acids, PFCAs and PFSAs most commonly become ionic compounds in the environment. For this reason the two compound classes generally have low volatility (Niva, 2007; ATSDR, 2009). This is opposed to the PFC compound groups FTOHs, perfluoroalkyl sulfonamides and sulfonamidoethanols, which are categorized as neutral volatile chemicals (Muller et al., 2012). For example PFOS has an estimated vapor pressure of 3.31 x 10^{-4} Pa (Poulsen et al., 2005; Environment Canada, 2012), while the two perfluoroalkyl sulfonamide compounds N-EtFOSEA (N-ethyl perfluorooctane sulfonamidoethyl acrylate) and N-MeFOSEA (N-methyl perfluorooctane sulfonamideethyl acrylate) have an estimated vapor

pressure of a factor 1000 times higher (5.04×10^{-1} Pa) than PFOS (Environment Canada, 2012). Muller et al. (2012) studied PFC concentrations in air of Zurich city in Switzerland, and measured high concentrations of FTOH in the air. 8:2 FTOH was the dominant compound of 24 measured PFCs with average concentration of 700 pg/m^3, and it was only detected in the gas phase.

2.6 Human exposure

The fact that a chemical substance is released in the environment does not always lead to human exposure. Typically exposure happens by one or several of pathways, like drinking contaminated water, eating contaminated food, breathing contaminated air or skin contact with contamination and contaminated products. For perfluoroalkyl compounds the main human exposure pathway are thought to be contaminated drinking water and food (ATDSR, 2009), especially seafood has been found to be a significant source of exposure (Haug et al., 2010). However, a myriad of different consumer products contributes to the total exposure, like the household products that are treated with stain or water repellent, hair care products, Teflon cookware etc. (Betts, 2007). In a recent study, 115 different PFCs were detected in paper and packaging for food, and PFCs were found to migrate from the different materials used for food contact (Trier et al., 2011). As perfluoroalkyl compounds have been detected in both air and dust, breathing of contaminated air is likely an important pathway of exposure (ATSDR, 2009; Haug et al., 2011b; Goosey et al., 2012). For example, PFCs in indoor house dust were suggested to be a significant contributor to PFCs in human serum (Haug et al., 2011a). Trier et al. (2011) emphasizes the need for knowledge on which PFCs are currently being used, so that monitoring of the compounds with respect to human exposure can be more complete. There have, for instance, been found large variations in proportions of unidentified fluorinated chemicals in human blood samples from China. In samples from Guiyang, Beijing, and Shenyang more than 70 % of the total extractable organic fluorine concentrations were identified PFCs, while in samples from Jintan city only 30 % were identified compounds (Yeung et al., 2008).

Concentrations of PFCs in human serum and whole blood samples have been studied by many (Karrman et al., 2006; Karrman et al., 2007; Yeung et al., 2008; Haug et al., 2009; Lindh et al., 2012). Serum PFC concentrations in Inuit from Greenland were among the highest reported from a general population (Lindh et al., 2012). In the study PFC concentrations in serum from Inuit from Greenland and citizens of Poland and Ukraine was compared. PFOS and PFOA represented about 90 % of the total PFC concentrations in all populations, and mean levels for PFOS and PFOA were respectively 52 and 4.8 ng/ml in Greenlandic Inuit, 19 and 5.2 ng/ml in citizens of Poland, 8.1 and 1.9 ng/ml in citizens from Ukraine (Lindh et al, 2012). From different studies of serum concentrations in the U.S. general population, respective ranges of average concentrations for PFHxS, PFOA, PFOS were 1.5–3.9 ng/ml, 2.1–9.6 ng/ml, and 14.7–55.8 ng/ml (ATSDR, 2009). Yeung et al. (2008) state that there is a lack of conclusive information on the human health effects from PFCs at the levels reported in general populations.

2.7 Toxicology

PFCs are subjected to placental transfer from mother to foetus as well as postnatal milk transfer (Haug et al., 2011a; Folkehelseinstituttet, 2012). The compounds PFOS and PFOA have been detected both in blood of newborns and in breast milk (Betts, 2007). In a study of 665 pregnant women and their children, the level of PFOA concentrations in serum of the pregnant women was found to be positively associated with increased body mass index (BMI) and waist circumference in female offspring at 20 years age. There was a positive association between prenatal exposure to PFOA and serum levels of insulin and leptin. Insulin and leptin are biomarkers that could indicate overweight. This association was found in both female and male children, although not as significant for males (Folkehelseinstituttet, 2012; Halldorsson et al., 2012). Similarly Maisonet et al. (2012) studied PFCs in serum of pregnant women in connection with weight of their female children. In the study of 447 girls and their mothers, they found an average 140 g lower birth weight for the girls with higher exposure to PFOS before birth than the less exposed girls. These patterns were also found for PFOA and PFHxS.

At 20 months, the girls that had been exposed to higher levels of PFOS had higher body weights.

Studies performing testing on laboratory animals have shown large variations in animal responses to perfluoroalkyl acids. For example, the compound PFOA in laboratory female rats is eliminated in hours, in male rats it takes days before elimination and for monkeys it takes months. This can be compared to a persistence of almost four years for PFOA in the body of humans. Generally, the longer carbon chain, the longer PFCs persist in the body. Perfluorobutane sulfonate (PFBS), with a four carbon chain, stays around one month in the human body before it is eliminated. While PFOS and PFOA, both with eight carbon chains, are eliminated after 5.4 and 3.8 years respectively. This generality is, however, not followed by perfluorohexane sulfonate (PFHxS), which has a six carbon chain and stays around 8.5 years in the body before it is eliminated. Animal studies have also given evidence that PFOS and PFOA have caused disruption in the hormone secreting system, developmental delays, increased morality of newborns and carcinogenic effects (Betts, 2007; Lindh et al., 2012). High doses of PFOS in rats and monkeys have lead to enlarged size and weight of the liver (3M, 2003), and liver cancer (Betts, 2007).

3. Description of the selected airports

The shape and geology of the Norwegian country is a challenge for the accessibility of many communities. Aviation has become an important way of accessing all parts of the country, and Avinor has developed a broad spatial distribution of airports. This has resulted in unique geological and environmental surroundings at the individual airports. The geological settings are the background for the variations in soil characteristics, hydrogeology, and thus the spreading of PFCs released on the ground at each airport. The map of ***Figure 6*** shows the location of Avinors 46 airports were the three selected in this study are underlined.

Figure 6: Map of Norway showing the spatial distribution of Avinors 46 airports (Avinor, 2012a).

The three airports selected for soil sampling are located near Bergen (Flesland), Kristiansund (Kvernberget) and Kristiansand (Kjevik). The airports are described in this section according to their location, general geology of the area, assumed water draining directions, the surrounding water bodies, and location and age of the fire training sites. The airports where chosen as they have soil types with large variations in geochemical characteristics which can influence the leaching and sorption behavior of different PFCs. It was important that the soils collected for laboratory experiments had high concentrations of PFOS (around 1000 μg/kg), allowing good detection limits in the leaching tests. In connection with the mapping of ground and groundwater pollution at Avinors airport facilities in 2011, reports were prepared for each airport by Sweco AS and COWI (Avinor, 2011b; Avinor, 2011c; Avinor, 2011d). Maps and general descriptions summarizes here. Results of analysis of soil, water and biota from the different airports summarizes in appendix A, for further details is referred to these references.

3.1 Bergen airport Flesland

Bergen airport Flesland is located in the western part of Norway, about 15 km from the city centre of Bergen. The terrain is mountainous, and the geology in the area is dominated by gneisses. The bedrock is generally covered by a thin layer of organic rich soil, and some places marsh. Fjords are surrounding the airport in three different directions. In the west is Raunefjorden, in south Fanafjorden and in north Gristadfjorden. Groundwater from the airport is draining in both east and west direction. In west direction it reaches the Raunefjord, while in east direction it can reach two different freshwater bodies, Lake Langavatnet and Lake Skjenatjørna. The two lakes are marked in the overview picture of the airport in ***Figure 7***. In Kvitura, Northwest of the airport, private groundwater wells are used for water supply. After measurements of the water in 2011 showed PFOS concentrations at a maximum level of 176 ng/l. Although below levels that could be asscocitated with a health risk (300 ng/L) according to the Norweian Institute of Public Health, these groundwater wells have not been exploited for drinking water purposes (Avinor, 2011a). At Flesland the dominating wind direction is south-west to north-east.

Figure 7: Overview map of Bergen airport Flesland, with the old and new fire training sites (FTS) marked.

Bergen airport has two fire fighting training sites, one is abandoned, and one is in use today. The abandoned training site was used in the time period 1957 to 1993, while in 1995 the use of the new training site began. Both the old and the new training sites are marked in ***Figure 7***, as FTS old and FTS new respectively. Samples for laboratory experiments were collected at the new training site, where high concentrations of PFOS in soil (up to 8250 µg/kg at) were reported (Avinor, 2011c). The recipient of surface water and groundwater from the new fire training site is assumed to be Lake Langavatnet, located between the airport runway and the FTS new in ***Figure 7***.

3.1.1 Soil sampling at Flesland

Samples for laboratory experiments were collected on the 18.05.2012 at the new FTS, used since 1995. Bedrock in the area of the new training site consists of alternating variations of gneisses, and the vegetation on the bedrock consists of a thin layer of organic rich forest soil. The training platform is located on a slight elevation in the terrain, and surrounded by conifer forest. Water and chemicals are collected at the platform and lead to the municipality waste water treatment plant (which does not treat water for PFOS) through the sewer pipelines. The platform with the aircraft body has a diameter of 30 m, and can be seen in the map of ***Figure 8*** as a circle with a brown object on. This map (in North-South direction) shows all sites previously sampled (Avinor, 2011c), where the three sites that were sampled for laboratory batch and column experiments are framed in black and white (BP3, BP7 and BP13).

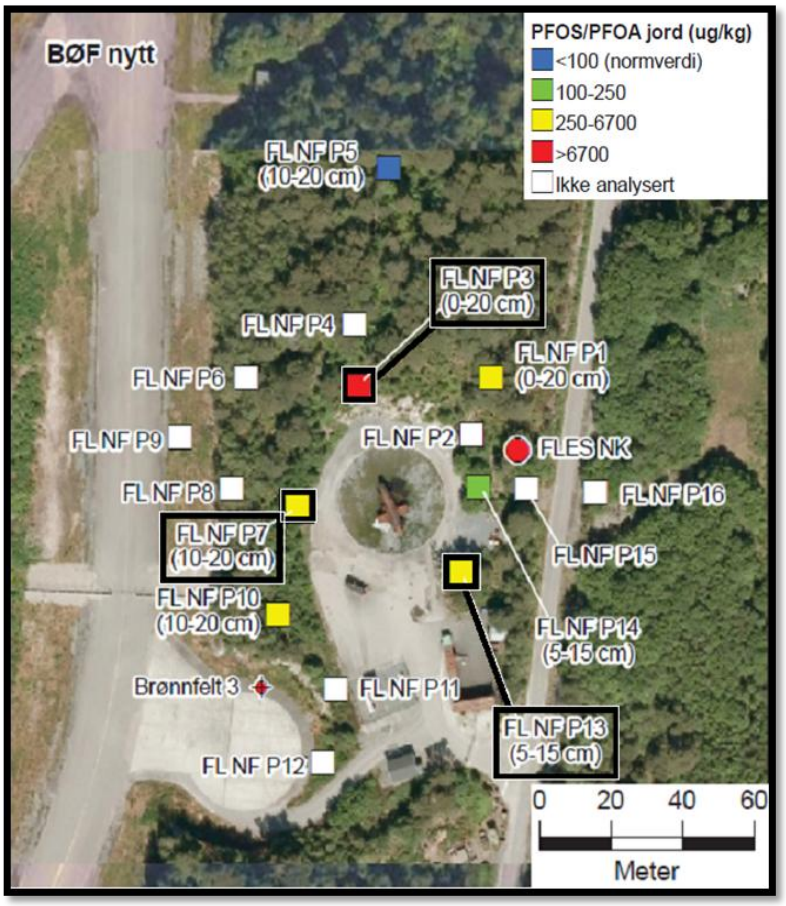


Figure 8: A map of the new fire fighting training station with all previously sampled sites showed (Avinor, 2011c). Soil samples were taken at the three sites marked FLNFP3, FLNFP7 and FLNFP13 in the map.

The new samples were taken in three different directions relative to the center of the platform, at sites that showed concentrations of PFOS >1000 µg/kg from previous analysis. All the soil samples were dug from depths between 0-20 cm using a stainless steel shovel, and stored in polypropylene (PP) bags. The sample depth and soil description for the specific sites is shown in ***Table 2***. Site BP3 is located by the blue barrel circled in ***Figure 9***, in north direction. The airport fire personnel use the barrel as a mark to aim their extinguisher at during fire fighting training on the aircraft body. Expecting a high concentration of PFCs, soil samples for batch experiment and repacking of columns were collected at this site. The soil was mostly dark brown with high content of roots, and events of lighter brown sticky soil. Site BP7 is located in the west direction of the aircraft body. This site had higher content of rocks in the soil. Site BP13 is located in the east direction of the aircraft body, on a slight elevation of the bedrock. At this site the soil layer was only 10-15 cm thick and exclusively dark black color. Pictures of the soil at the three sites are shown in appendix A.

Table 2: Sample type, name of site, depth (cm) of sampling, and a short description of the soil type for soil samples from the new FTS at Bergen airport.

Soil samples at the new FTS			
Sample type	**Sample site**	**Depth (cm)**	**Soil type**
Soil for repacking of cylinders and batch experiment	B P3	0-10	Organic rich forest soil, dark brown color, high root content, events of lighter clay soil
Soil for batch experiment	B P7	10-20	Organic rich forest soil, dark brown color, high root content, more small rocks
Soil for batch experiment	B P13	0-15	Organic rich forest soil, dark black color

Figure 9: Picture of the aircraft body used for firefighting training, site BP3 is located by the blue barrel (red circle) in the background. The edge of the circular platform is visible in front.

3.2 Kristiansund airport Kvernberget

Kristiansund airport Kvernberget is located on the island Nordlandet in the western part of Norway. The distance to the city center of Kristiansund is about five km. The dominating landscape surrounding the airport is a rolling mountain terrain. Kvernberget is a mountain in the north direction, while in south direction is the seawater body Ormsundet. An overview picture of the airport is shown in ***Figure 10***. The airport drains towards the sea by three river brooks; Orvikabekken, Byskogbekken and Gløsvågbekken. The depth to groundwater is between 1-4 meters in the east, and 0-2 meters in south. Dominating wind direction is from south or south-west.

Kristiansund airport has one new and one old fire fighting training sites, both are shown in ***Figure 10*** as FTS new and FTS old. The new site was finished in 2004, and is the only training site used today. The material for laboratory experiments was sampled at the old fire fighting training site of this airport.

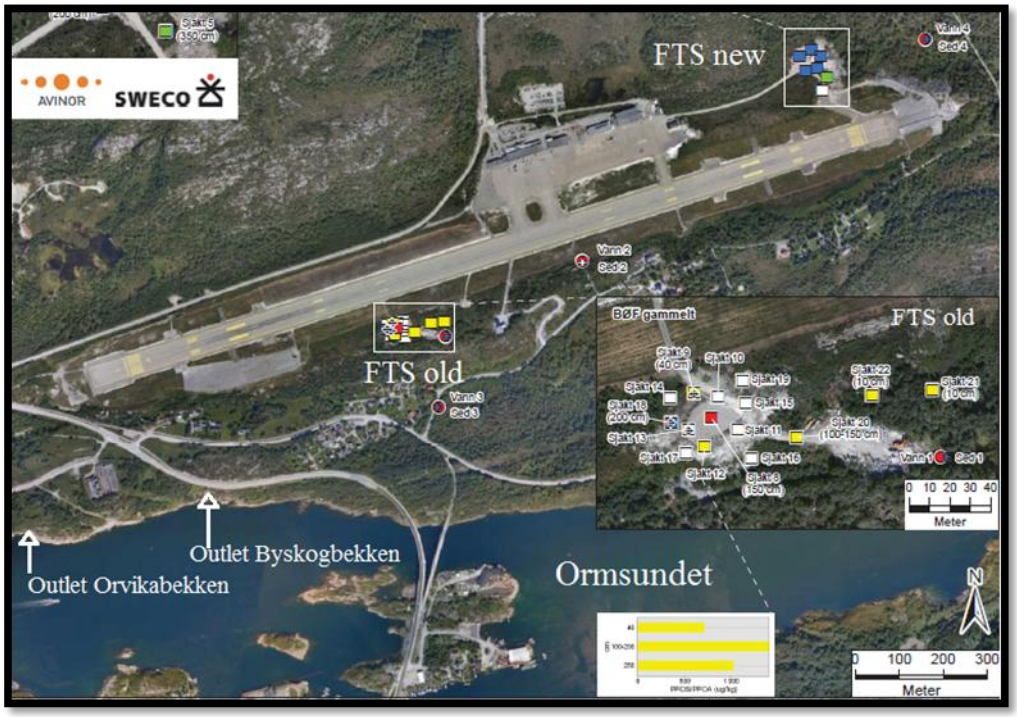


Figure 10: Overview map of Kristiansund airport Kvernberget, with the old and new fire fighting training sites (FTS) marked.

3.2.1 Soil sampling at Kvernberget

The field work was performed on 22.05.2012, at the old fire fighting training station used until 2004. At this fire fighting training station around 500 m^3 soil materials was replaced after 2002, and the existing material is a mix of rocks, gravel and sand from blasting (see ***Figure 12***). The material has large variations in size, and in the central part of the training site it is overlying bedrock at a depth of about 1-2 meters. In the eastern part of the site the bedrock is exposed, and in south and west peat soil is dominating at 1-2 meter depth. Groundwater is expected to drain towards the sea in direction of Ormsundet. The central part of the training site can be seen as the largest grey circular area on the map of ***Figure 11***. This map shows all sites previously sampled (Avinor, 2011b), and the site that was sampled for laboratory batch and column experiments are located between the two sites framed in black and white on this map.

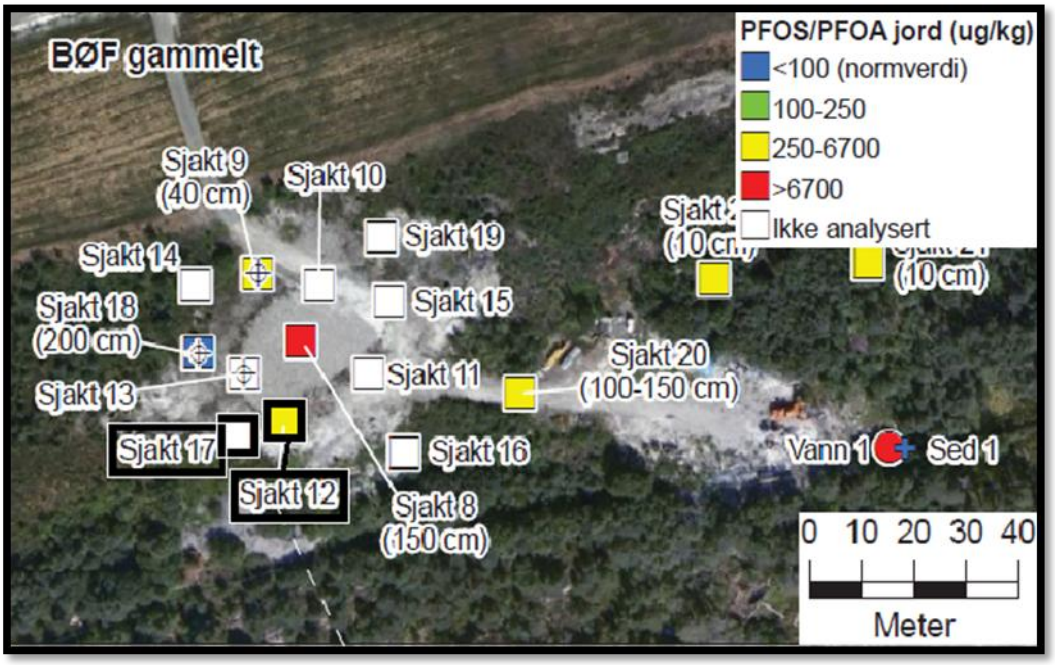


Figure 11: A map of the old fire fighting training station with all previously sampled sites showed (Avinor, 2011b). Soil samples were collected in a shaft dug with an excavator, between the two sites marked Sjakt 12 and Sjakt 17 in the map. The new shaft was named shaft 12:17.

Figure 12: Picture of the old FTS where the soil material was replaced after 2002. The picture is taken towards the south direction, where the trial pit named shaft 12:17 was dug close to the trees by the orange cone in the background of the photo.

The aim of the sampling was to collect natural peat with a high concentration of PFOS. An excavator was used to dig the trial pit for sampling, and natural peat was found at 185 cm. Two stainless steel cylinders with diameter 7 cm and length 87 cm were pressed into the natural peat, and they were filled with 52 cm and 63 cm of soil material. The excavator was used to dig the cylinders out, and the total depth of the trial pit was 257 cm. During the excavator work some soil material from the top of the trial pit fell into the cylinders, and plugs were put into them to avoid contamination. For batch experiments two polypropylene (PP) bags were filled with soil from 200-250 cm depth of the trial pit.

Table 3: Soil type, name of site, depth (cm) of sampling, and a short description of the soil type for soil samples from the old FTS at Kristiansund airport.

Soil samples at the old FTS			
Sample type	**Sample site**	**Depth (cm)**	**Soil type**
Cylinder KSU A	Shaft 12:17	185 - 272	Natural peat
Cylinder KSU B	Shaft 12:17	185 -272	Natural peat
Soil for batch experiment	Shaft 12:17	200-250	Natural peat, dark brown and black color, sticky with high content of degraded organic material

The first 185 cm of the trial pit named shaft 12:17 was a mix of rocks, gravel and dark brown organic rich soil. This is likely material from the replacement of the soil performed at the FTS around year 2002. The natural peat found at 185 cm and larger depth had a dark brown and black color. The peat was sticky and seemed to have a high content of degrading roots and deteriorating organic material (see ***Figure 13***). A short summary describing the soil type at the site and the depth of sampling is in ***Table 3***.

Figure 13: The natural peat had high content of degrading roots and deteriorating organic material (left). The soil profile (right) can be seen in the trial pit, total depth was of the shaft was 257 cm.

3.3 Kristiansand airport Kjevik

Kristiansand airport Kjevik is located in the southern part of Norway, about 16 km northeast of the city centre of Kristiansand (Avinor, 2012c). Overview map of the airport is shown in ***Figure 14***. The landscape where the airport is located is a river terrace, with an elevation of circa 15 meter above sea level. Subsurface material in the area has from previous borings proven to be sandy soil with a depth of 1-2 meters, covering silt and clays at larger depth. Groundwater is generally found at shallow depths, and some places it is at about one meter. The groundwater in the area drains towards the river Topdalselva in east direction and Ålefjærfjorden in the southeast direction. Groundwater in this area is not exploited.

Figure 14: Overview map of Kristiansand airport Kjevik, with the two abandoned fire fighting training sites (FTS) marked.

Kristiansand airport has three fire fighting training sites, whereas two are no longer in use, the third was established in 2008 and is used today. It is located in the west direction towards the fjord, under the enlarged map of FTS 1985-2008 in ***Figure 14***. Both the old fire fighting training sites are located alongside the river Topdalselva in east direction of the runway, marked as FTS until 1985 and FTS 1985-2008 in ***Figure 14***. The oldest of them was used until 1985, and the use of the other abandoned site was from 1985-2008. Soil from both the older fire fighting training sites was sampled for laboratory experiments.

3.3.1 Soil sampling at the site used until 1985, Kjevik

Figure 15: Excavation work on shaft 15, assumed to be the central part of the training station. The pile of masses in front of the excavator has been placed at the site after the use of the training station ceased.

The field work at the fire fighting training station used until 1985 was performed on the 05.06.2012. The exact location of the training site is not known. As there is no visible training platform at this site, the training might not have been limited to one single spot. Excavation work has been done in the airport area, and masses have been placed at the old training station. The original soil from the time the station was used is still conserved, but some places overlaid by these masses from another location. The soil material at the training station consists of sand in varying colors like black in the topsoil (upper 50 cm), and yellow, grey, and brown at depth. At depths larger than 1-2 meter silty clays can be found. The groundwater

drains towards the river Topdalselva with a difference in height of about 10 meters. The map of ***Figure 16*** shows all sites previously sampled (Avinor, 2011d), and the site sampled for laboratory batch experiment is framed in black and white (Shaft15).

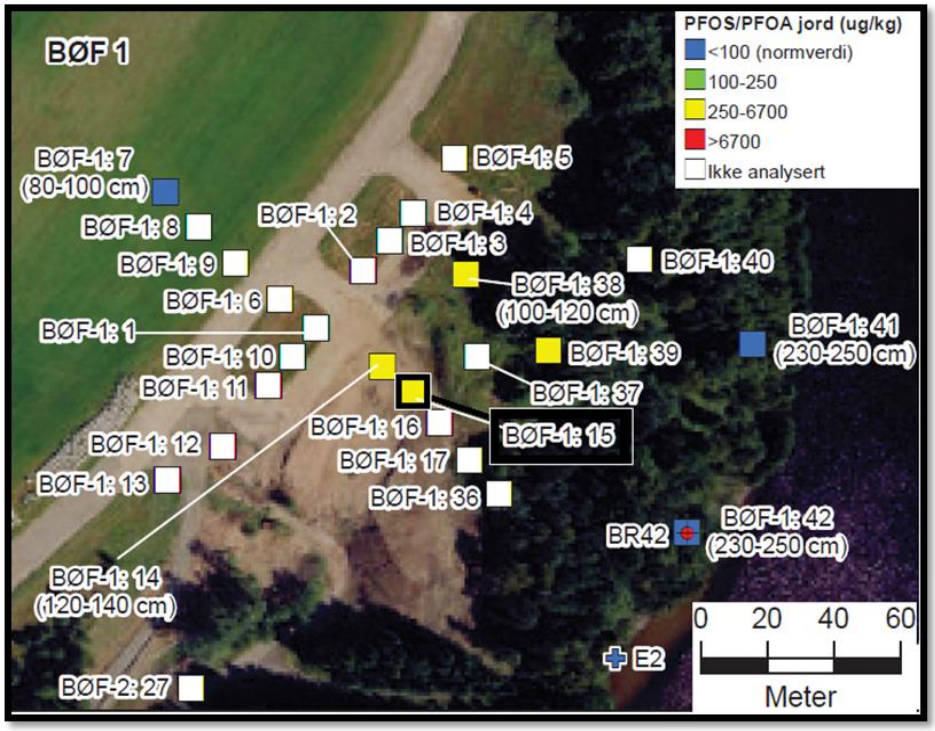


Figure 16: A map over the fire fighting training station used until 1985 with all previously sampled sites shown (Avinor, 2011d). Soil samples were taken at the site marked BØF-1: 15 in the map.

Figure 15 shows excavation work in trial pit 15 where the soil samples for laboratory batch experiments was collected. The pile of masses that can be seen in front of the excavator in the picture has been placed at the site after the use of the training station ceased. The upper of masses 0.5-1 m of soil was removed before sampling to ensure that sampling was in original soil from the station. One sample was taken at 50 cm depth, and the other was taken at 80-85 cm depth (see ***Table 4***). The soil profile and the trial pit down to 85 cm can be seen in ***Figure 17***.

Table 4: Sample type, name of site, depth (cm) of sampling, and a short description of the soil type for soil samples from the FTS used until 1985.

Soil samples at FTS used until 1985			
Sample type	**Sampled site**	**Depth (cm)**	**Soil type**
Soil for batch experiment	BØF-1:15	50	Sand, dark brown and black color.
Soil for batch experiment	BØF-1:15	80-85	Sand, dark brown and black with events of red color.

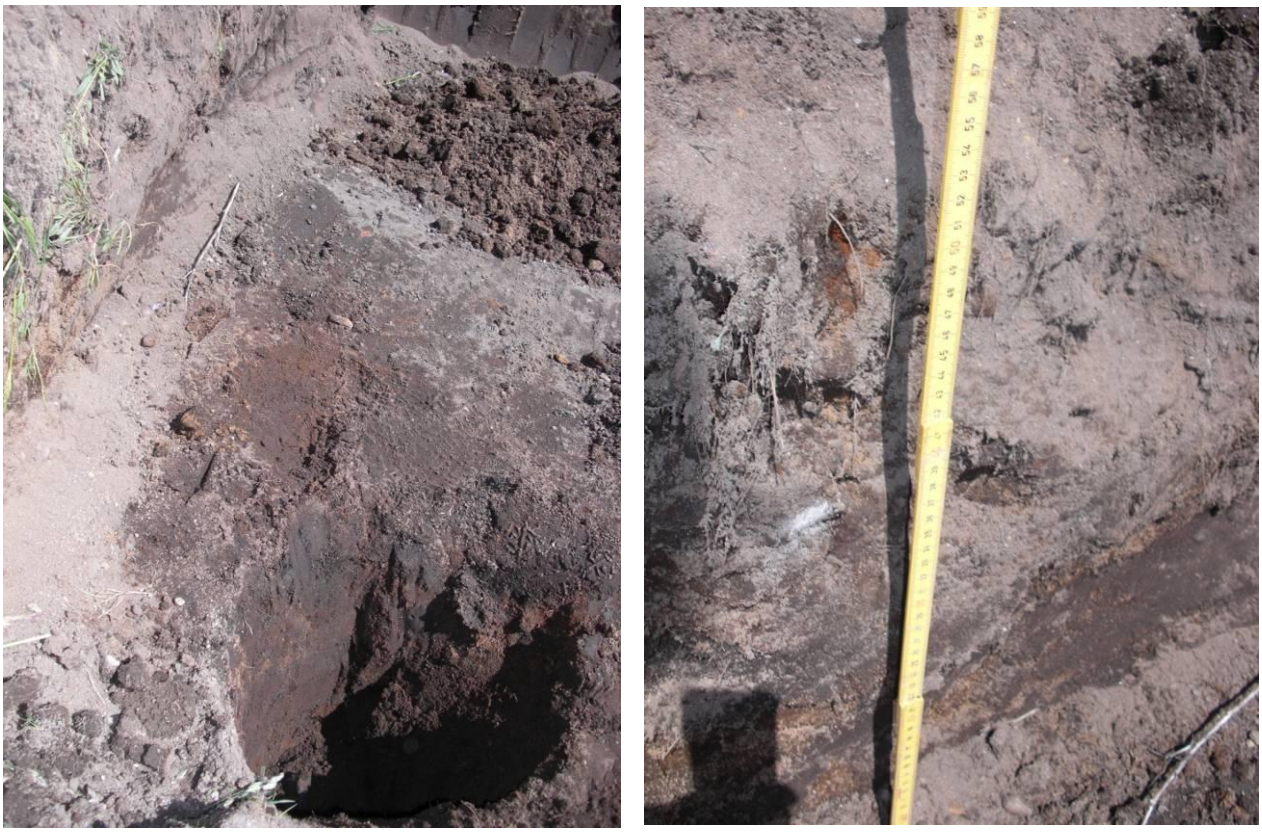


Figure 17: The soil profile of trial pit 15 at FTS used until 1985 (left), 0.5-1 meters of soil was removed before sampling to make sure the soil was the original from the training station. The soil type is sand with a dark brown and events of red color (right), the total depth of the trial pit was 85 cm.

3.3.2 Soil sampling at the site used from 1985 to 2008, Kjevik

Figure 18: The training platform of FTS 1985-2008 is filled with green colored water. Picture is taken in north direction. The oldest FTS (until 1985) is located at a slightly higher level up the road seen in the middle background.

The field work at the fire fighting training station used in the period 1985-2008 was performed on the 05.06.2012. The training station is located at a lower level than the oldest FTS (until 1985), and not more than around 4-5 meters higher than the river Topdalselva. In direction of the river there is a conifer forest. The groundwater drains towards the river, and close to the platform the groundwater level is at about 2.5 meters depth. The training platform was built in 2000, and is therefore relatively new ***Figure 18***. The soil material at the training station consists of sand in varying colors like black in the topsoil (upper 10 cm), red, yellow, grey, and brown at depth. The map of ***Figure 19*** shows all sites previously sampled (Avinor, 2011d), and the site sampled for laboratory batch experiment is framed in black and white (Shaft 30).

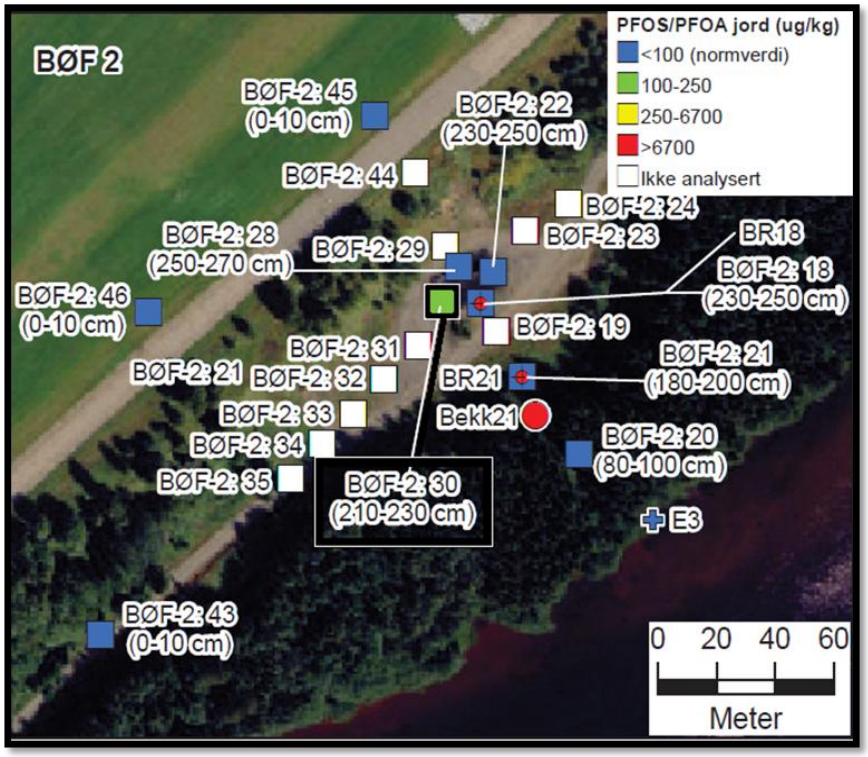


Figure 19: A map of the fire training station used between 1985 and 2008 with all previously sampled sites shown (Avinor, 2011d). Soil samples were taken at the site marked BØF-2: 30 in the map.

Before performing the sampling at this FTS the material filled in around the platform was removed using an excavator (upper 80 cm). The excavator pressed the two stainless steel cylinders for laboratory column experiments into the red colored sandy soil as showed in ***Figure 20***. The total length of the columns was 88 cm, and they were both filled with 46-47 cm of soil. A soil sample for batch experiments was collected using a stainless steel shovel, and stored in a PP bag. The sampling depths and short soil descriptions are given in ***Table 5***. The red sand and the soil profile of the trial pit is shown in ***Figure 20***, total depth of the trial pit was around 100 cm.

Table 5: Sample type, name of site, depth (cm) of sampling, and a short description of the soil type for soil samples from FTS used from 1985 to 2008.

Soil samples at FTS 1985-2008			
Sample type	**Sample site**	**Depth (cm)**	**Soil type**
Cylinder KSA A	Shaft 30	80-167	Sand
Cylinder KSA B	Shaft 30	80-167	Sand
Soil for batch experiment	Shaft 30	80-100	Sand, red and brown color.

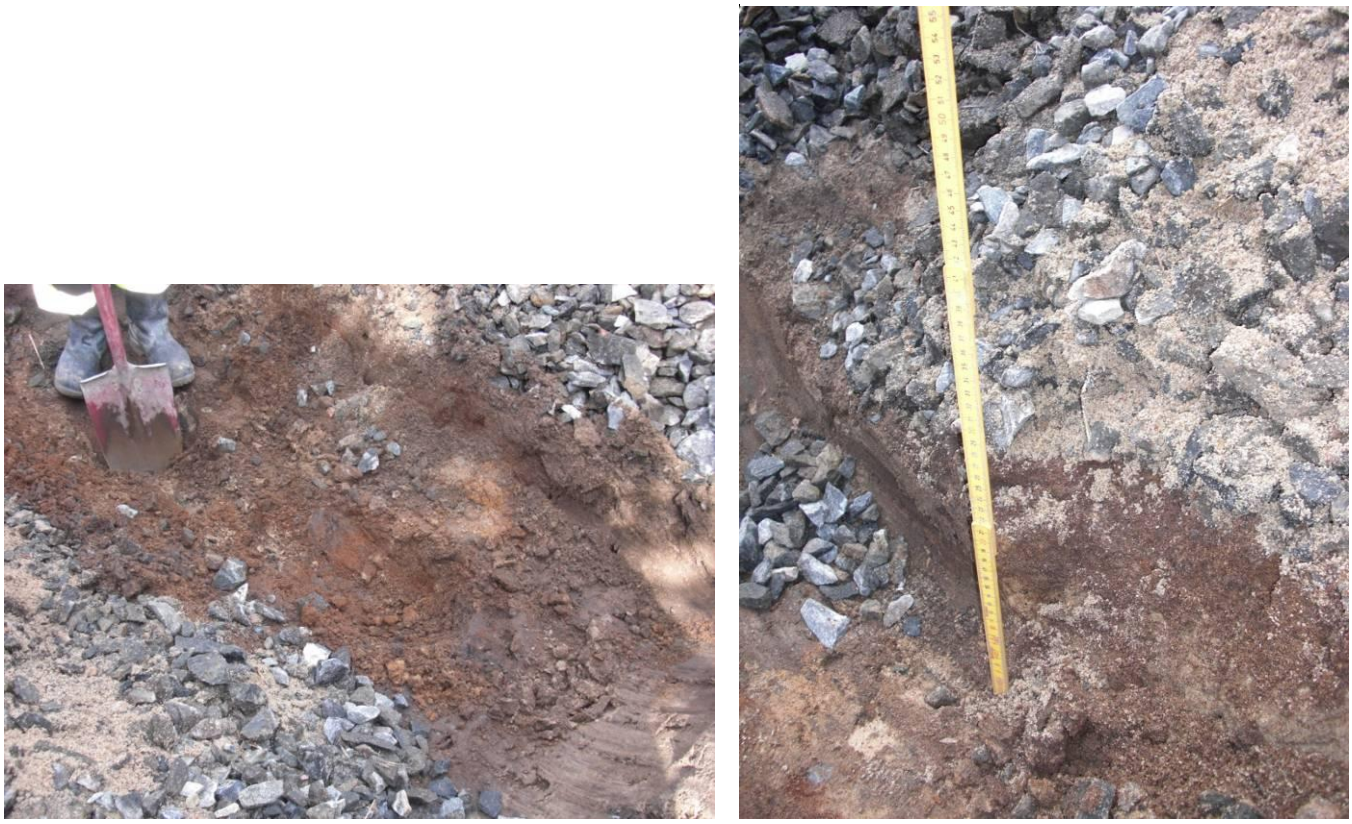


Figure 20: The red and brown colored soil material that was sampled for batch and column experiments in trial pit 30 at FTS 1985-1998 (left). Soil profile of trial pit 30, coarse material filled in around the platform was removed down to the sandy soil (right).

4. Methods

4.1 Soil characterization

The seven soil samples were continuously stored in 10 °C from the day of collection, and were before further use homogenized by mixing. Water content was determined using subsamples in triplicate for each soil type, and weighing them before and after drying at 110°C. Analysis of total carbon (TC) and total organic carbon (TOC) was done in duplicates. Two grams of dry soil from each of the seven samples was crushed, and 0.35 g (x2) of this was run in a LECO carbon analyzer for TC analysis. For TOC analysis 0.35 g (x2) of soil was treated with acid (HCl) at 40-50 °C in a crucible to remove the inorganic carbon. To prevent chlorides causing corrosion in the LECO instrument, the soil was then washed with distilled water. After drying completely the samples could be run in the LECO carbon analyzer. Due to high organic content, only one sample from each of the sites BP13 and KSU was analyzed for TOC. The results of water content, TC, TOC and TIC for the seven soil samples are in ***Table 6***.

Table 6: Water content, total carbon, total organic carbon and total inorganic carbon of the seven soil samples.

Soil sample	µ water content %	µ TC %	µ TOC %	µ TIC %
B P3	117	11.0	9.51	1.47
B P7	62.1	10.2	8.55	1.62
B P13	328	46.2	45.7	0.50
KSUND	383	44.7	43.2	1.56
KSA 15 A	18.4	1.94	1.66	0.28
KSA 15 B	17.1	1.37	1.36	0.01
KSA 30	10.9	0.37	0.21	0.16

From 200 to 300 g of each of the seven homogenized soil samples was analyzed for the concentrations of PFCs before the laboratory experiments. The soil was analyzed for a total of

12 compounds. 10 of them were perfluoroalkyl compounds, and 2 were fluoroteleomers. The acronyms, compound names and structures of the compounds analyzed for in soil (n = 7) are shown in ***Table 1***. This includes 6:2 Fluoroteleomersulfonate (FTS), 8:2 Fluoroteleomer sulfonate (FTS), Perfluorobutane sulfonate (PFBS), Perfluorobutanoic acid (PFBA), Perfluorodecanoic acid (PFDA), Perfluorohexane sulfonate (PFHxS), Perfluorohexane acid (PFHxA), Perfluoroheptanoic acid (PFHpA), Perfluorononanoic acid (PFNA), Perfluoroctanoic acid (PFOA), Perfluoroctane sulfonate (PFOS), Perfluoropentanoic acid (PFPeA), and 16 different elements/metals (see appendix B for details).

4.2 Batch experiments

All water samples in the batch experiment were analyzed for the same 12 PFCs and 16 elements/metals as described for soil samples. Water samples were also analyzed for dissolved organic carbon, and the anions Cl^-, NO_3, SO_4, and PO_4 (see appendix B for details). All samples were sent for analysis the same day they were filtered. One filter was used pr 0.5 l water, and the samples were preserved and sent for analysis in 1 liter glass bottles with all caps covered in aluminum.

Figure 21: Soil samples mixed with Millipore water was placed on the end-over-end shaker.

The dissolution of the soil in Millipore water was first tested in the laboratory using one dry and one wet sample of each soil type. Samples were placed on an end-over-end shaker ***Figure 21*** at 10 rpm for 4-5 days, and after this the content was allowed to settle out by gravity. The dry soils were found not to dissolve completely for the samples with high organic content, while the soil containing its natural water content dissolved sufficiently. Based on this test the soil was not dried before the partitioning experiments. The batch experiments were carried out in triplicates for the seven different soil types. A liquid to solid ratio (L/S) of 10 was used, and 150 g soil and 1500 g water was added to 2.0 L PP bottles. To prevent roots and larger mineral grains to enter the PP bottles, soil samples KSA 30, KSA 15 A and B, BP3 and BP7 were sieved through 2.00 mm sieves. The samples BP13 and KSUND were not sieved through the 2.00 mm sieve due to their sticky character. For BP3 a 4.00 mm sieve was used, and for KSU the soil was thoroughly checked by hand. The water content of each soil type was used in the process of weighing out soil samples for the experiments. As an example the water content ($\frac{\Delta \text{ weight of wet and dry soil}}{\text{weight of dry soil}}$) of soil from BP3 was 117 %, this gives (1.17 x 150 g dry soil) + 150 g dry soil = 325 g of wet soil added to the PP bottle. The 1500 g of liquid then consisted of Millipore water and the water naturally contained in the soil.

4.2.1 Batch number 1

Batch number 1 consisted of one sample in triplicate with soil from KSA 30. For the compounds in the soil samples KSA 30 to reach equilibrium partitioning between soil and water, the total time of contact between water and sediment in the PP bottle was determined to be 10 days (Higgins et al., 2006). The samples of batch 1 were placed on the end-over-end shaker at 10 rpm over a period of 10 days. Immediately after shaking the water phase was centrifuged at 5000 rpm for 15 min, and filtered through 0.45 µm Supor-450 membrane filters (142 mm) (polysulfone filter) using a stainless steel pressure filterer (no Teflon surfaces) (see ***Figure 22***).

Figure 22: The stainless steel pressure filterer used to filter all water samples.

4.2.2 Quality control

Millipore water was spiked with PFOS and PFOA for quality control. The individual standard solutions of PFOS and PFOA were acquired from CHIRON AS. 1.1 ml containing 50 µg/ml of each substance in Methanol was mixed with 8.3 l Millipore water. One sample in triplicate was refrigerated at 10 °C with no treatment before it was analyzed. The other sample in triplicate went through the exact same treatment as for the soil samples of batch 1.

The untreated spiked samples had an average concentration of 4.5 µg/l PFOS and 5.76 µg/l PFOA. If all PFOS and PFOA were extracted from the individual standard solutions and mixed with the water, the water should have a concentration of 6.6 µg/l PFOS and 6.6 µg/l PFOA. The difference in concentration of 32 % for PFOS and 13 % for PFOA could be a result of the standard solutions not being completely extracted out of the packaging with the pipette. In addition it is likely that molecules are adhering to the walls of the glass bottle, and

from the differences in concentrations it is clear that PFOS is most affected. 3M (2003) reported that PFOS adheres to container surfaces.

Results of the quality control were the background for some changes in the further procedure. The PFOS/PFOA spiked sample that was filtered through Supor-450 filter showed a recovery of 57.3 % for PFOS and 96.9 % for PFOA (***Table 8***). Acceptable recoveries are normally between 50-150 %, whereas lower or higher recoveries results are considered not so reliable (Klif, 2010). It is likely that the filter is responsible for much of the loss of PFOS. A comparative test using two different filter types was conducted to examine the loss of PFOS. Two soil samples in triplicates from site KSA 30 was shaken for four days, one was filtered through Whatman GF/C glass fiber filters, and the other through Supor-450 filters. In addition one single sample of Millipore water spiked with standard solutions of PFOS and PFOA, and was filtered through Whatman GF/C glass fiber filter. In this experiment the highest concentration of PFOS was found in water filtered through glass fiber filter. This water also had higher concentration of dissolved organic carbon (DOC) than the water filtered through Supor-450 filter. Higher concentration of DOC could affect the water concentration of PFOS as the substance could be bound to the particle surfaces in the solution (3M, 2003).

Figure 23 is a scatter plot of concentrations of water PFOS and DOC for the sample KSA 30 of batch 1, filtered by Sulfone-450 (Polysulfone 1), together with concentrations for the two comparative samples of KSA 30, filtered with different filter types (GF/C and Polysulfone 2). This plot shows that the sample polysulfone 2 of the comparative test has the lowest concentrations of PFOS and DOC, while the sample of batch 1 (Polysulfone 1) has the highest concentration of PFOS and DOC. From the small difference in the relation of PFOS/DOC for these two samples (***Table 7***) it is likely that the increase in PFOS concentration can be explained by the increase in DOC. Comparing the relation for all of the three samples (***Table 7***), GF/C filter has the highest relation compared with the two samples where Sulfone-450 filter had been used. This indicates that the increase in DOC concentration could not solely explain the increase in concentration of PFOS for GF/C filter. All average PFOS and DOC concentrations, standard deviations and relation between average PFOS and DOC concentrations is shown in ***Table 7***.

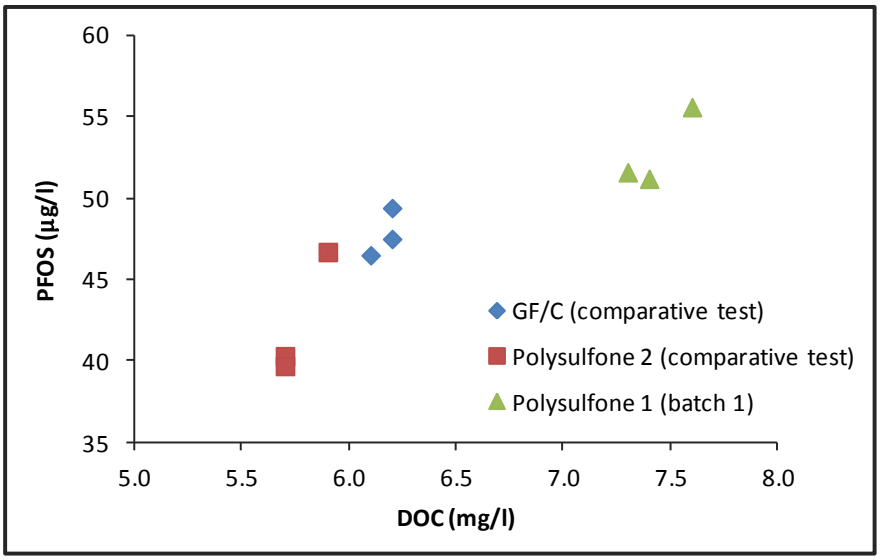


Figure 23: Scatterplot for the PFOS concentration (µg/l) and DOC concentration (mg/l) in water of batch 1 and the comparative filter test.

Table 7: Results from the comparative test for the two different types of filter, polysulfone and GF/C filter.

Filter type	Sample name	Average PFOS µg/l	Average DOC mg/l	St.dev. PFOS µg/l	St.dev. DOC mg/l	PFOS/DOC
GF/C	KSA 30-F (comparative test)	47.8	6.2	1.5	0.06	7.8
Supor-450	KSA 30-S (comparative test)	42.2	5.8	3.9	1.12	7.3
Supor-450	Ksand 30 (batch 1)	52.8	7.4	2.4	0.15	7.1

The single spiked sample was highly supportive for the results of the comparative test, with a recovery of 81.7 % for PFOS using glass fiber filter. Based on this the final choice of filter type for the next batches was decided to be the glass fiber filter. Results for the recovery percentage of PFCs for glass fiber filter compared to Supor-450 filter are shown in ***Table 8***.

Table 8: Mean concentrations (ng/l) and recoveries (%) for spiked untreated samples, spiked sulfone filtered samples and the spiked GF/C filtered sample.

Parameter	Mean concentration, no treatment	Mean concentration, Sulfone filter	Concentration, Riste GF*	Recovery sulfone filter %	Recovery GF/C filter %
6:2 FTS	< 7.5	< 7.5	< 7.5	n.d	n.d
8:2 FTS	< 10	< 10	< 10	n.d	n.d
PFBS	< 7.5	< 7.5	< 7.5	n.d	n.d
PFBA	12.4	12.7	< 5	103	< 40.3
PFDA	< 5	< 5	< 5	n.d	n.d
PFHxS	127	123	109	96.6	85.8
PFHxA	< 5	< 5	< 5	n.d	n.d
PFHpA	22.6	21.3	22.7	94.1	100
PFNA	< 5	< 5	< 5	n.d	n.d
PFOA	5763	5587	5470	96.9	94.9
PFOS	4517	2587	3690	57.3	81.7
PFPeA	< 5	< 5	< 5	n.d	n.d
Sum PFC excsl. LOQ	10467	8330	9290	79.6	88.8
Sum PFC incl. LOQ	10467	8377	9340	80.0	89.2
Sum PFOS/PFOA excsl LOQ	10267	8177	9160	79.6	89.2
Total PFOS/PFOA incl LOQ	10267	8177	9160	79.6	89.2

* one single sample. n.d = no data as the compound were under limit of quantification.

Due to the high content of suspended solids in the sample of batch 1 it was determined that the next batches in the experiment should be placed for sedimentation of particles in minimum two days. The number of days for shaking the samples was equally reduced to maintain the contact time of 10 days. The fact that more than four days contact was needed for equilibration was supported by samples from the comparative test. As described, soil from KSA 30 was used for the first batch, and for the comparative test. Samples with a contact time of four days (filtered with sulfone filter) had 20 % lower total concentrations of PFCs in water.

4.2.3 Batch number 2 and 3

Figure 24: Particles left on the GF/C filter after filtration of the water samples.

Batch number 2 consisted of two samples in triplicate using soil from KSA 15A and KSA15B. Batch number 3 consisted of two samples in triplicate using soil from BP3 and BP7. The following procedure was used for batch number 2 and 3:

For mixing of soil and water, the samples were placed on the end-over-end shaker at 10 rpm over a period of eight days. After this the samples were moved to a horizontal surface for the suspended solids to settle out by gravity. Difficulties with filtering the water phase of some samples prevented the scheduled progression, as an example ***Figure 24*** shows the suspended particles left on the GF/C filter of sample BP3-1. This resulted in a prolonging of the total time of contact between water and sediment, originally determined to be 10 days, with 1-4 days for samples in this batch. The water was filtered through Whatman glass fiber filters using a stainless steel pressure filterer (no Teflon surfaces).

4.2.4 Batch number 4:

Batch number 4 consisted of two samples in triplicate using soil from BP13 and KSUND. After shaking for eight days, the samples of batch 4 were treated differently than as described for samples above. Suspended particles did not settle out for these samples, and separation of the soil and water phase was challenging. As an attempt to break down the organic fibers in the soil, and ease the settling of particles, the samples were frozen. Different methods were tested out after thawing, and finally all the samples were first hung in a nylon filter-net over a glass container of 3000 ml. Gravity filtration yielded about 500 ml liter of water for all samples in the batch, and by squeezing the soil an additional 200-300 ml could be extracted for BP13 samples and 50-100 ml for KSUND samples. For KSUND the soil in the filter-net was moved to a 1 liter glass container, and filtered again using a steel filter with pressure weights on top. This yielded another 50 ml of water, and a total of 600-700 ml of water was sent for analysis for all samples of the batch.

4.2.5 Calculating K_d and K_{oc} values

K_d values for PFC compounds in the different soil samples were calculated using the average soil concentrations (µg/kg), and equilibrium water concentrations (µg/l) from the batch experiments. For compounds with concentrations lower than limit of quantification (LOQ) in both soil and water, K_d could not be estimated. For compounds quantified in water, with concentration lower than LOQ in soil from a site, K_d was estimated to be < the calculated value. For compounds quantified in soil, with concentration lower than LOQ in water sample, K_d was estimated to be > than the calculated value. An example of how to calculate K_d in these cases would be:

$K_d = \frac{C_s}{C_w} = \frac{10}{<1} = > 10$, and $K_d = \frac{C_s}{C_w} = \frac{< 10}{1} = < 10$

K_{oc} is the partitioning coefficient for organic carbon and water. It was found by normalizing K_d for the fraction of organic carbon in the soil: $Koc = \frac{Kd}{foc}$

4.3 Column experiments

Column experiments were performed using the undisturbed soil columns sampled with stainless steel cylinders at Kristiansund and Kristiansand airport fire training sites. In addition, top soil (10-20 cm) from Bergen was repacked into stainless steel cylinders. The experiment was carried out in parallels for the three different soil types; sand (Kristiansand), peat (Kristiansund) and organic rich forest soil (Bergen). Experimental setup of the soil columns are shown in ***Figure 25***, the average air temperature in the room was 4 ºC throughout the experiment.

Figure 25: The experimental setup of soil columns in the laboratory. The experiment simulates vertical infiltration of precipitation from the top soil towards the depth of the soil profile. The columns are placed upside down with the water inlet at the bottom so that the soil become completely water saturated, and air bubbles are eliminated.

The experiment simulates the vertical infiltration of precipitation from the top soil towards the depth of the soil profile. For the soil in the cylinder to become completely water saturated, the cylinders are placed upside down with the water inlet at the bottom, avoiding air bubbles in the soil.

At Bergen airport the soil around the fire training site was a very thin layer of organic rich soil. Due to difficulties of taking undisturbed soil profile samples at this site, the collected top soil (10-20 cm) was repacked in the laboratory. Two stainless steel cylinders (diameter 7 cm and length 88 cm) were packed with soil from site BP3 of the fire training station. The packed soil contained its natural moisture content (from the time of sampling), and was divided into 5 equal portions. For each portion filled into the column, the soil was compressed using a piston. For the two other sites, columns were used undisturbed as collected during field work (described in section 3.).

At the top and bottom of all columns, the soil was capped with Whatman GF/C filters (150 mm Ø). The GF/C filters were then capped with close meshed nylon nets, and finally plugs were inserted and tightened. To plug the columns in both ends, plugs in plastic material (containing no Teflon surfaces) were used. Tubes inserted to the inlet and outlet of the plugs consisted of nylon, while the tubes going through the pumps were silicon material. The nylon tubes (due to their rigidity) cannot be used for the peristaltic pumps. A total of four pumps were used in the experimental setup to pump Millipore water through the columns. The parallel columns from Bergen had one pump together, the parallel columns from Kristiansand also had one pump together and the parallel columns from Kristiansund had one pump each. This allowed water flow velocity for columns from Kristiansund to be adjusted individually, while for the other parallel columns only minor individual velocity adjustments was possible. Since several of the parallel columns had common pumps, the average dry weight of soil (solid) in the parallels was used for calculating the amount of liquid to flush through each column. The dry weight of soil (g) in columns was estimated using the water content of the soil (4.1 Soil characterizations). The wet weight of soil (g), dry weight of soil (g) and the estimated amount of liquid (ml) at an intended liquid to solid ratio of 10 for the parallel columns are shown in ***Table 9***. Given the varying densities of the different soil types, the total amount of water to flow through each column in the time of the experiment is also varying. The experiment was over a period of 35 days (almost 5 weeks) starting 09.10.2012 and ending 13.11.2012. ***Table 9*** show the measured total liquid amount and average flow-velocity of the columns, estimated mineral bulk density and porosity of the soil, and the total number of flushed porevolumes. During the experiment the leaching water from the soil columns was sampled at the five L/S ratios 2, 4, 6, 8, and 10. The measured total amount of water compared

to the estimated/intended total amount of water, the difference was within 93-111 % for all columns except those from Kristiansund. The water flow was very slow through these columns, and a total amount of water equivalent to an L/S ratio 5.5 and 6 went through (53 % and 64 % of L/S 10). The porevolume of the soil could be found by the difference between the weight of the soil columns when they were water saturated, and the dry weight of the soil in the columns. The mineral bulk density and porosity of the soil was estimated from the dry weight of the soil.

Table 9: Height (cm) and weight (g) of the 6 soil columns used in the column experiment. Dry weight of the soil (solid) is calculated from the water content (%) of the soil. Estimated total liquid (ml) is the total amount of water needed for an intended liquid to solid ratio of 10.

Soil column	KSA30-A	KSA30-B	BP3-A	BP3-B	KSU-A	KSU-B
Height of soil column (cm)	47	46	64	70	46	50.5
Volume of soil column (cm^3)	1809	1770	2463	2694	1770	1943
Weight of wet soil (g)	3917	3250	2340	2303	2740	2544
Water content %	11	11	117	117	383	383
Amount of solid in column (dry weight) (g)	3532	2930	1080	1063	567	526
Mineral bulk density (g/cm^3)	1.95	1.66	0.439	0.395	0.320	0.271
One porevolume (ml)	717	703	2436	2398	3447	2213
Porosity of soil	0.203	0.240	2.26	2.26	6.08	4.20
Water in porespace of natural wet soil (ml)	54	45	52	52	63	91
Estimated total liquid (ml)	35320	29305	10803	10632	5671	5265
Measured total liquid (ml)	33017	32662	10770	10819	3642	2773
Total amount of days	35	35	35	35	35	35
Estimated average flow-velocity (ml/h)	42.0	34.9	12.9	12.7	6.75	6.27
Measured average flow-velocity (ml/h)	39.3	38.9	12.8	12.9	4.34	3.30
Total porevolumes	46.0	46.5	4.4	4.5	1.1	1.3

Elute from each column was collected in individual glass bottles. As the three different soil types had relatively large differences in total amount of water (ml), and thus water velocity, the sampled liquid fractions also had large variations. For elute from sandy soil the collecting bottles had a volume of 10 liters, for elute from organic rich forest soil the bottles had a volume of 5 liters, and for elute from peat soil the bottles had a volume of 2 liters. For parallel columns with soil from Bergen and Kristiansund, subsamples of elute from the L/S ratios 2, 4, 6, 8, and 10 were collected. For parallel columns from Kristiansund, the velocity of water through the columns slowed down during the entire experiment. Air bubbles were observed in the outgoing tube of the columns, and this might indicate that microbiological degradation and gas development was occurring. One of the parallels had a velocity of 1.5-1.9 ml/day during the last two weeks of the experiment, and liquid fraction of L/S ratio 2, 4 and 4.5 was possible to collect. For the other parallel, subsamples of elute from the L/S ratio 2, 4, 6 were collected.

All subsamples of water during the experiment were analyzed for the same 12 PFCs and 16 elements as described for soil. Water samples were also analyzed for DOC and the anions Cl^-, NO_3, SO_4, and PO4 (see appendix C for details). The procedure when taking a subsample from elute collected in each bottle at a given L/S ratio was: 1. noting the date and precise time of sampling, 2. weighing and homogenizing the liquid fraction, and 3. transfer the subsamples of each liquid fraction to 1 liter glass bottles and 0.5 l plastic bottles. The bottles were stored in 4 °C until they were sent for analysis simultaneously.

4.4 Mass balance calculations

Mass balance calculations for the PFC compounds were performed. This was to examine the amount of the individual PFCs that had leached out of the initial amount in soil. For batch experiments the amount of the individual PFCs in soil from each site was calculated using the concentrations in soil, and the dry weight of soil added to the mixing bottles. The amount of the individual PFCs in water samples after batch experiments was calculated from the water concentrations, and the volume of water added to each bottle. For column experiments the initial amount of individual PFCs in soil of each column was estimated using the concentrations in soil and the dry weight of soil in each column. The amount of the individual

PFCs in leachate over time was calculated from the concentrations in leachate and the volume of water collected at each L/S ratio.

4.5 Data treatment

Excel was used as the tool for all data treatment. When examining linear correlations in the data, the data was plotted in a scatter plot, and the “trend line options” function was used for setting intercept, displaying the equation, and displaying the R-square value.

5. Results

5.1 Soil characterization

The results of the soil characterization are summarized in ***Table 10***. The samples in the table are ranged according to their increasing TOC percentage, except for KSA 15 A and B that are samples taken from the same site at different depths. All of the other samples are from individual sites. The ΣPFC concentrations in the samples are shown in the ***Table 10***.

Table 10: A summary of soil characterizations for the seven different sampled sites. The ΣPFC concentrations excludes the limit of quantification (LOQ) (µg/kg dw).

Parameter	KSA 30	KSA 15 A	KSA 15 B	BP7	BP3	BP13	KSUND
Soil type	Sand			Organic rich forest soil			Natural peat
Training station active	1985-1998	Until 1985		From 1995			Until 2004
Depth of sampling (cm)	80-100	50	80-85	10-20	0-10	0-15	200-250
TOC %	0.21	1.66	1.36	8.55	9.51	45.7	43.2
Water content %	10.9	18.4	17.1	62.1	117	328	383
foc	0.002	0.017	0.014	0.085	0.095	0.457	0.432
Ca (mg/kg dw)	970	1167	937	2867	2800	3567	7500
Mg (mg/kg dw)	730	850	770	6000	2400	1700	1400
CEC							
ΣPFC concentration in soil excl. LOQ (µg/kg dw)	733	490	268	905	5501	464	477

The ΣPFC concentration (µg/kg dw) are average of the quantified concentrations in three subsamples (n=3) of the soil from each site. Results from the analysis of all the PFC compounds in the soil samples are shown in Appendix B.

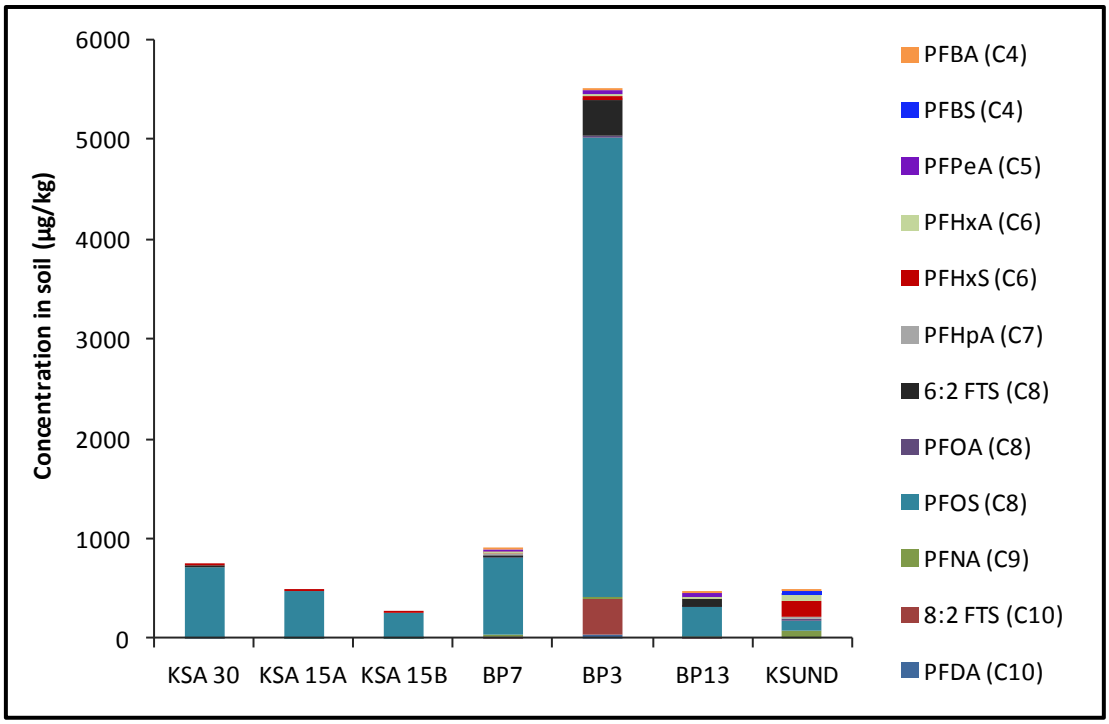


Figure 26: Concentrations (µg/kg dw) of PFCs in the seven soil samples organized according to increasing carbon chain length of the individual PFCs (average of n=3).

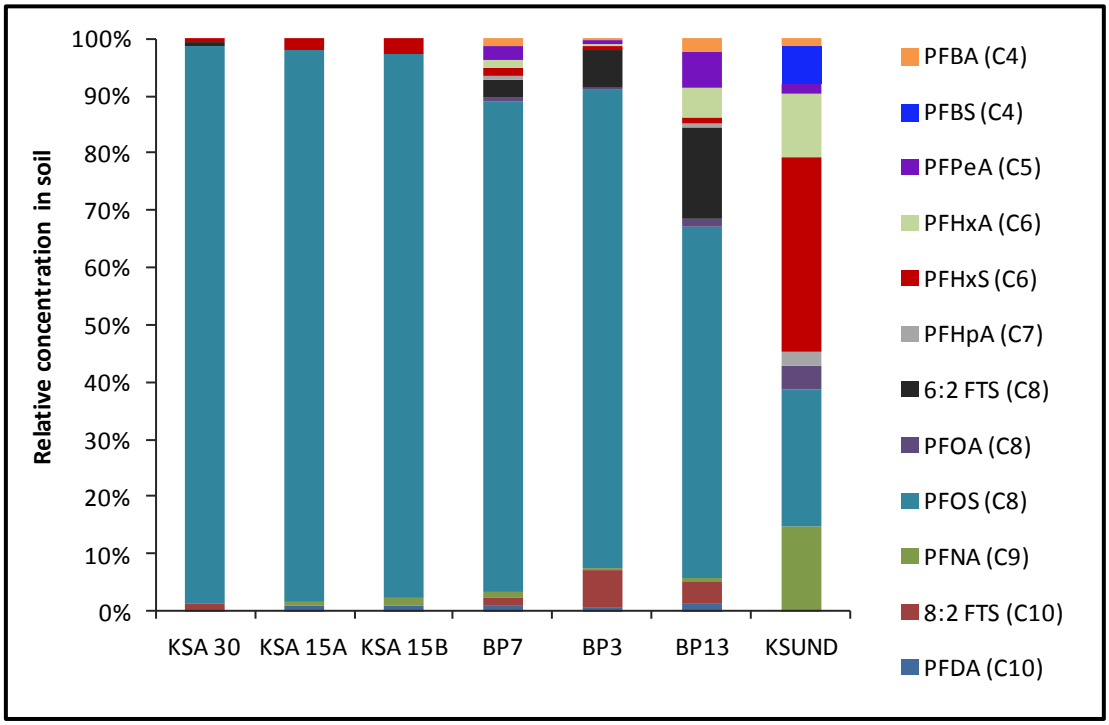


Figure 27: Relative contribution (%) of individual PFC concentrations to the ΣPFCs in soil samples used in the laboratory experiments, organized according to increasing carbon chain length (average of n=3).

Figure 26 shows the average concentration and distribution of the quantified PFC compounds in the different soil samples. The highest total concentration of PFCs (5501 µg/kg) was found in organic rich forest soil from Bergen sample BP3. The lowest total concentration (268 µg/kg) was in sandy soil from Kristiansand sample KSA 15 B (at 80-85 cm depth). It is clear that PFOS is the dominating compound in all samples, except in the sample from Kristiansund where PFHxS was found to be dominating. The highest concentration of PFOS was found in Bergen sample BP3 (4603 µg/kg), six times higher than the second highest concentration which was measured in the Bergen sample BP7 (776 µg/kg), and 18 times higher than for the lowest concentration which was measured in the Kristiansund sample KSUND (255 µg/kg).

The relative distribution of PFCs in the soil samples (see ***Figure 27***) shows that all samples from Kristiansand mainly contain PFOS. In sample KSA 30 the compound 8:2 FTS has the second highest concentration (1.2 %), and the compounds 6:2 FTS and PFHxS are also present (< 1%). In samples KSA 15 A and B there is a minor contribution of PFHxS (2.1 % and 2.6 % respectively), PFNA and PFDA (< 2%). Bergen samples have a considerable contribution of many PFCs, most prominent after PFOS is the compounds 6:2 FTS and 8:2 FTS. In sample BP3 the compounds 6:2 FTS and 8:2 FTS together are contributing with 13 %. In sample BP7 the highest relative contributions apart from PFOS are 6:2 FTS (3.1 %), PFPeA (2.6 %) and 8:2 FTS (1.4 %). In sample BP13 6:2 FTS is contributing with 16 % of the total quantified PFC concentration. The sample from Kristiansund has a significant contribution of a variety of PFC compounds, dominated by PFHxS (34 %), PFOS (24 %) and PFNA (15 %).

5.2 Batch experiments

Average PFC concentrations (µg/l) in the water from batch experiments are shown in ***Figure 28***. The highest sum of PFCs was in the leachate of Kristiansand sample KSA 30 (54.7 µg/l), followed by Bergen sample BP3 (51.0 µg/l). The lowest sum of PFC concentrations was in Bergen sample BP13 (9.82 µg/l). The composition and relative distribution of PFCs (***Figure 29***) was very different in leachate of soil from the three airports. Samples from Kristiansand had PFOS as the dominating component, with a contribution of PFOS in the range from 91 to

97 % for the different samples. In samples KSA 15 A and B PFHxS contributed with around 6 %, other compounds contributed with < 1.1 % each. In samples KSA 30 the second highest contribution after PFOS was from 8:2 FTS (1.2 %). Water samples from Bergen had 6:2 FTS, PFOS, PFPeA, PFHxA as the dominating compounds. In samples BP3 and BP13 the main component was 6:2 FTS (54 % and 34 % respectively), while in sample BP7 PFOS had the highest concentration (44 %) followed by 6:2 FTS (16 %). BP3 also had relatively high concentration of PFOS (29 %), PFPeA (6.1 %) and PFHxA (4.3 %). BP13 had second highest concentration of PFPeA (25 %) and then PFHxA (16 %), while PFOS was only 8.9 % of the total concentrations in this sample. The Kristiansund sample contained PFHxS (39 %), PFHxA (23 %) and PFBS (15 %) as the most prominent compounds, with very little PFOS. The average filtered water concentrations (µg/l) and standard deviations of PFCs from batch experiments are shown in Appendix B.

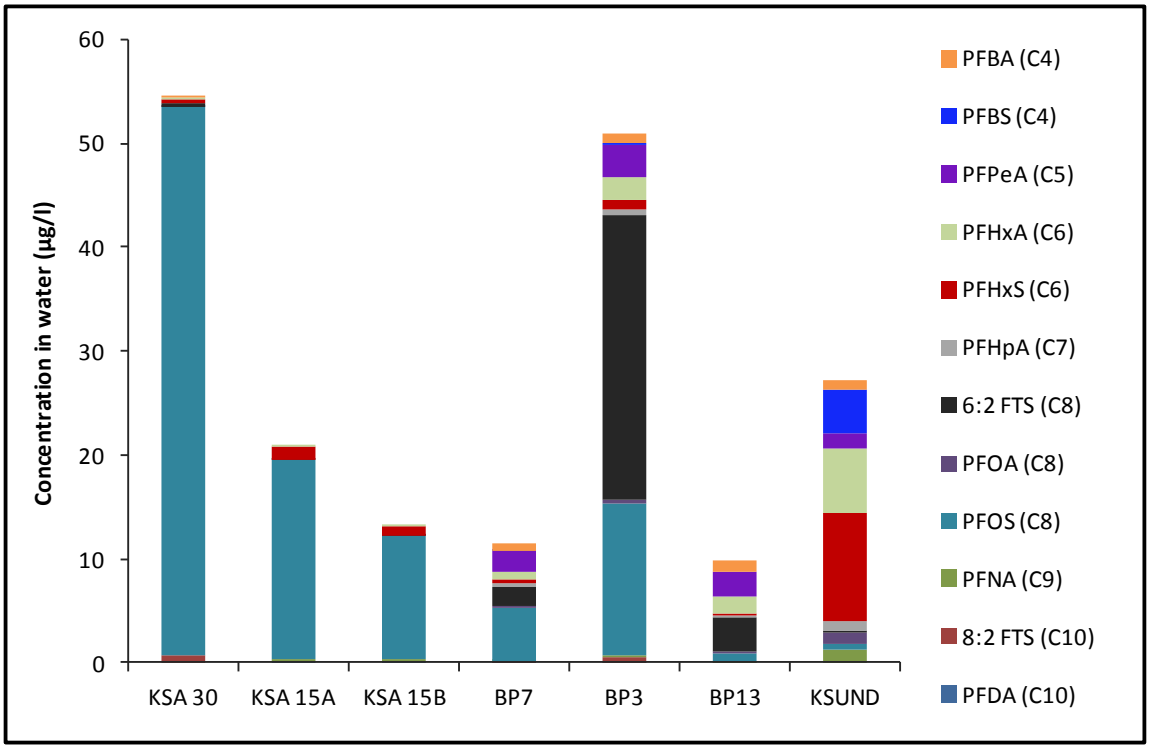


Figure 28: PFC concentrations (µg/l) in filtered water from batch experiments with the seven different soil samples, organized according to increasing carbon chain length (average of n=3, Ksund n=2).

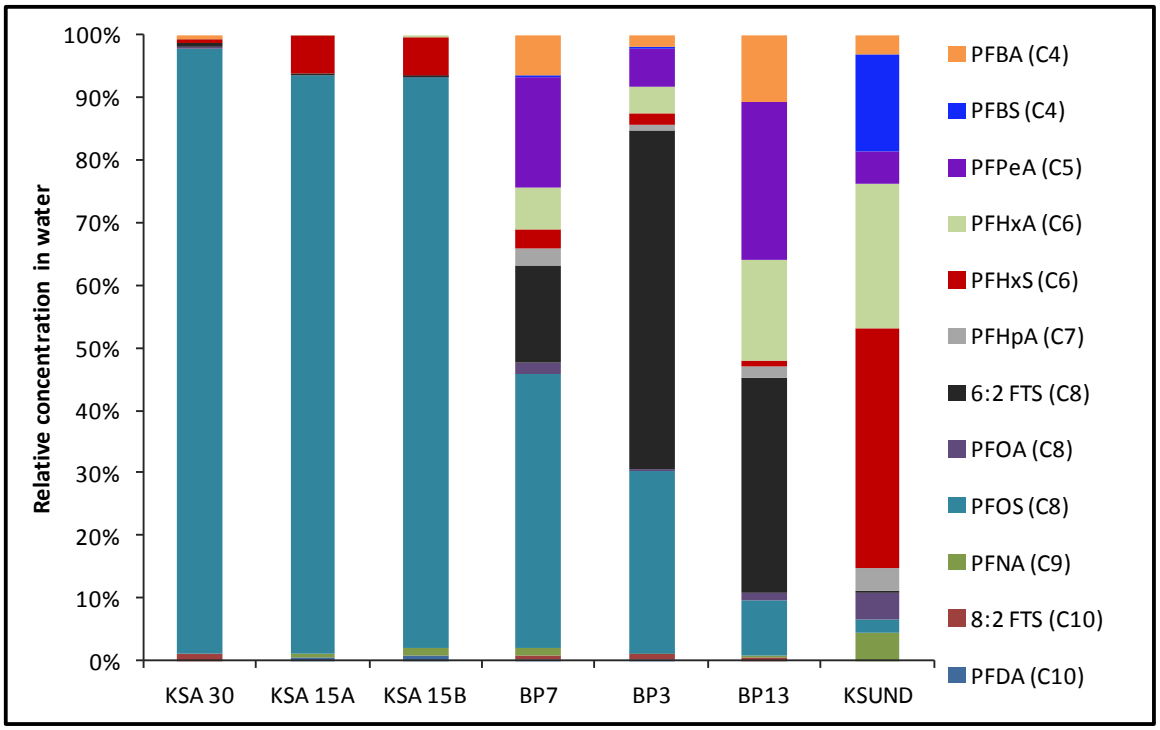
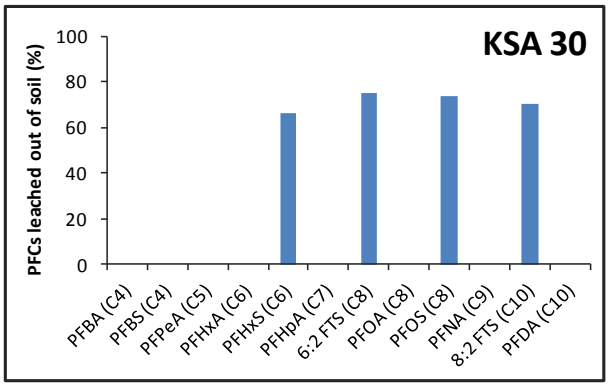
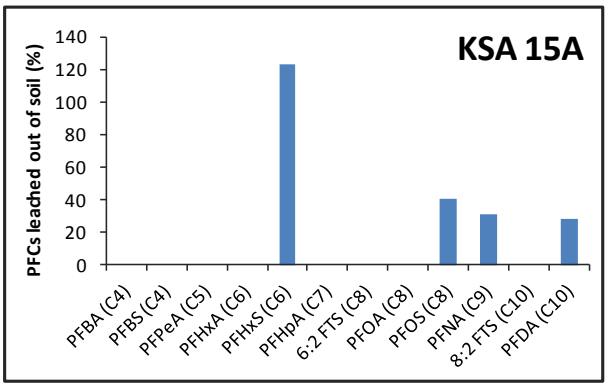


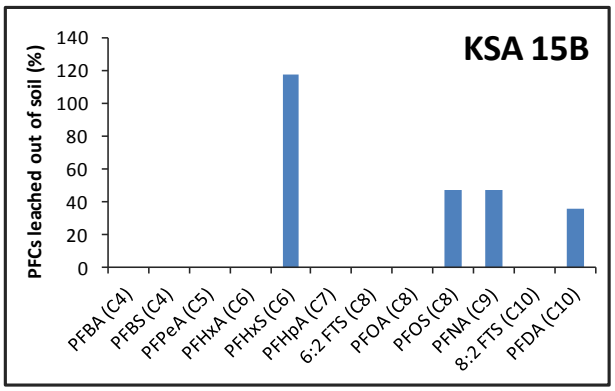
Figure 29: Average proportions (%) of PFC concentrations to the ΣPFCs in filtered water samples from the batch experiments, organized according to increasing carbon chain length (average of n=3, Ksund = 2).

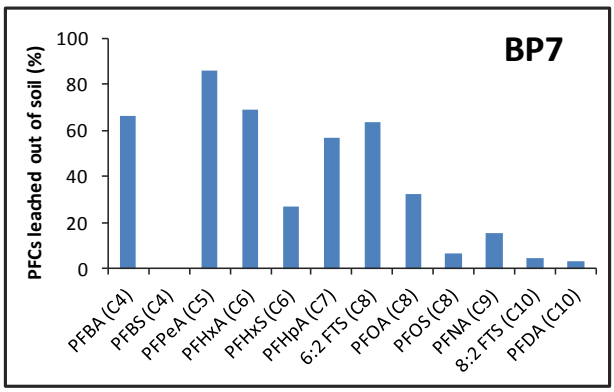
A mass balance for the 12 individual compounds was calculated. The percent of the individual compounds leached out from the initial content in soil are shown in ***Figure 30***. The percent leached out of soil could only be calculated for the compounds over the limit of quantification in soil. The four compounds in sample KSA30 leached out in very equal amounts from soil. The leaching for the individual compounds was in the range from 66 to 75 % of the total amount in soil. In the leachate of the two soil samples KSA15A and B, taken from different depths, both samples had high amounts of the total PFHxS, and low amounts of the total PFOS, PFNA and PFDA in soil. The amount of the individual PFCs leached out of soil samples BP7 and BP3, and BP13 are very similar; the compounds PFPeA, PFHxA and PFBA had leached out the most of the total content in soil, and PFDA (< LOQ in water sample BP13) and 8:2 FTS the least. For soil sample KSUND the compounds PFPeA, PFBA, and PFBS had leached out the most of the total content in soil, while PFOS had leached out the least.

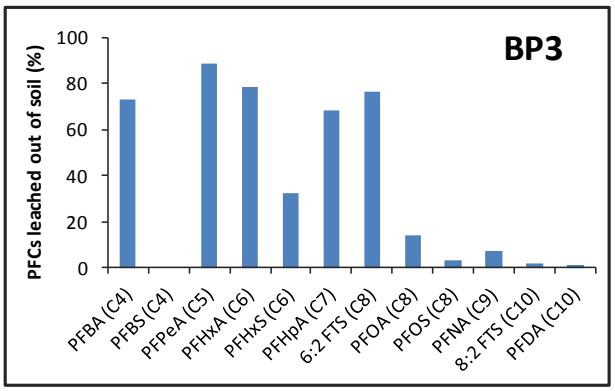
Figure 30: The amount of the individual PFCs in leaching water as percentage of total amount in soil from each site. The PFC compounds are organized according to increasing carbon chain length; carbon chain length is increasing from left to right.

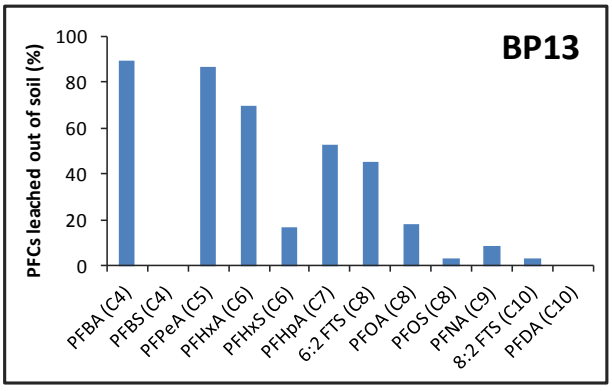


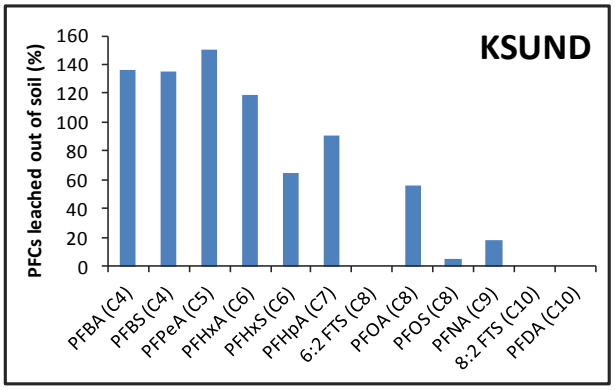












5.2.1 Soil - water partitioning coefficients (Kd values)

Using the average soil concentrations (µg/kg) and equilibrium water concentrations (µg/l) from the batch experiments, K_d values for PFC compounds in the different soil samples were calculated (see ***Table 11***). Calculated log K_d values together with K_{oc} and log K_{oc} values, based on the TOC content in the various soil samples, are shown in appendix B. The water at site KSA 30 was filtered with polysulfone filter, whereas the other samples were filtered using glass fiber filter (GF/C). As described in the method section polysulfone filter gave a lower recovery of PFOS spiked water.

Table 11: K_d values for the PFCs calculated from average quantified soil (µg/kg) and water (µg/l) concentrations of batch experiments. PFC compounds are ordered according to their carbon chain length. For compounds only quantified in either the soil or water sample, the LOQ value was used for estimation of K_d.

Kd values (l/kg)							
Compounds	**KSA 30**	**KSA 15A**	**KSA 15B**	**BP7**	**BP3**	**BP13**	**KSUND**
PFBA (C4)	< 6.67	n.d	n.d	15.1	13.7	11.2	7.34
PFBS (C4)	n.d	n.d	n.d	< 175	< 35	n.d	7.43
PFPeA (C5)	n.d	n.d	n.d	11.7	11.3	11.6	6.67
PFHxA (C6)	< 20	< 66.7	< 40	14.5	12.8	14.4	8.42
PFHxS (C6)	15.2	8.13	8.53	37.7	31.1	60.4	15.5
PFHpA (C7)	n.d	n.d	n.d	17.7	14.6	18.9	11.1
6:2 FTS (C8)	13.4	< 37.5	< 150	15.7	13.0	22.1	< 54.4
PFOA (C8)	< 16.7	n.d	< 117	30.9	70.4	54.9	17.8
PFOS (C8)	13.5	24.6	21.2	153	312	332	202
PFNA (C9)	n.d	31.9	21.3	66.0	145	119	57.0
8:2 FTS (C10)	14.2	n.d	n.d	220	711	294	n.d
PFDA (C10)	n.d	36.0	28.2	354	753	>212	n.d

n.d: k_d could not be determined since both concentration in soil and water were below LOQ.

Among all the calculated K_d values, the highest was 753 l/kg for PFDA in Bergen sample BP3. The lowest calculated K_d was 7.89 l/kg for PFPeA in the Kristiansund sample. Ranges of K_d values (l/kg) for all sampling sites presented in ***Table 12*** with the compounds according to increasing carbon chain length:

Table 12: Range of K_d values (l/kg) for all sampling sites with the compounds according to increasing carbon chain length.

Compounds	Highest K_d value	Lowest K_d value
PFBA and PFBS (C4)	7.34	15.1
PFPeA (C5)	6.67	11.7
PFHxA and PFHxS (C6)	8.13	60.4
PFHpA (C7)	11.1	18.9
6:2 FTS, PFOA and PFOS (C8)	13.0	332
PFNA (C9)	21.3	145
8:2 FTS and PFDA (C10)	14.2	753

5.2.2 Relative distribution of PFCs in soil and water

The relative contribution of PFCs in soil and water samples from Kristiansand (***Figure 31***) shows that PFOS is totally dominating in all samples. PFHxS contributes more to the ΣPFC concentrations in water samples relative to soil samples KSA 15 A and B. In samples from Bergen the compound 6:2 FTS, is very prominent in water relative to soil samples (***Figure 32***). The short carbon chain compounds (including 6:2 FTS) are very dominant in all water samples, composing in the range from 50 % to 90 % of the total concentration for the Bergen samples. The compound 8:2 FTS is most prominent in soil relative to water samples. In the water samples from Kristiansund (***Figure 33***) the short carbon chain compounds are also very dominant, and composing around 90 % of the total concentration. PFNA (C9) is the only compound with a carbon chain higher than eight that is observed in samples of Kristiansund.

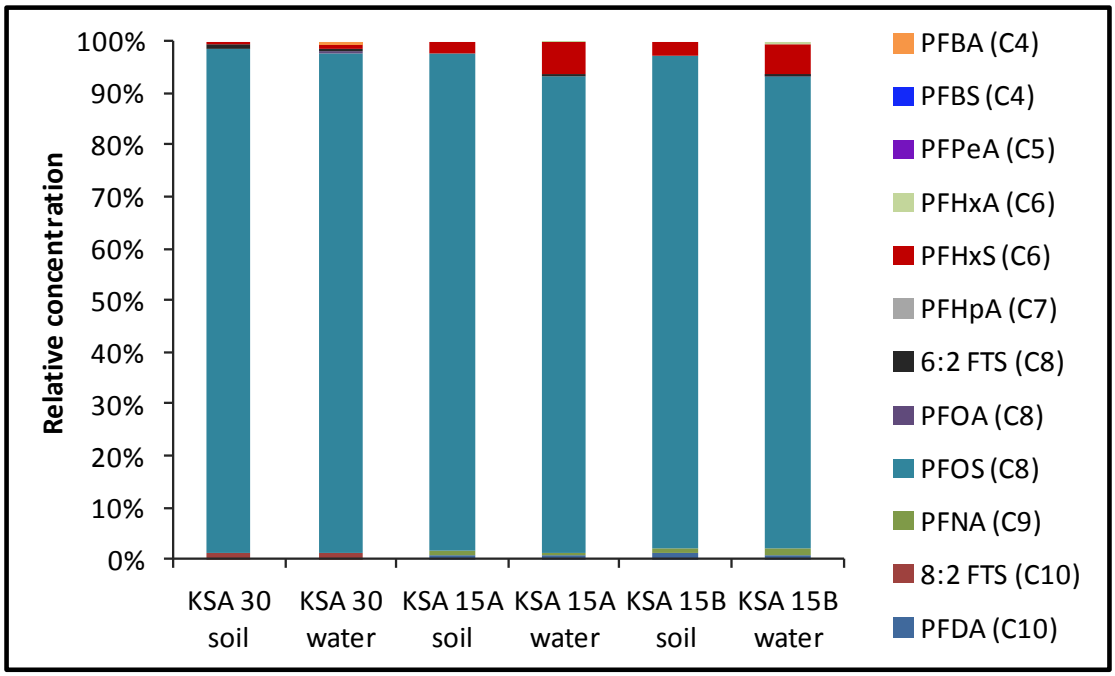


Figure 31: Relative average concentration distribution (%) of PFCs to the ΣPFC in soil and water from batch experiments with samples from Kristiansand.

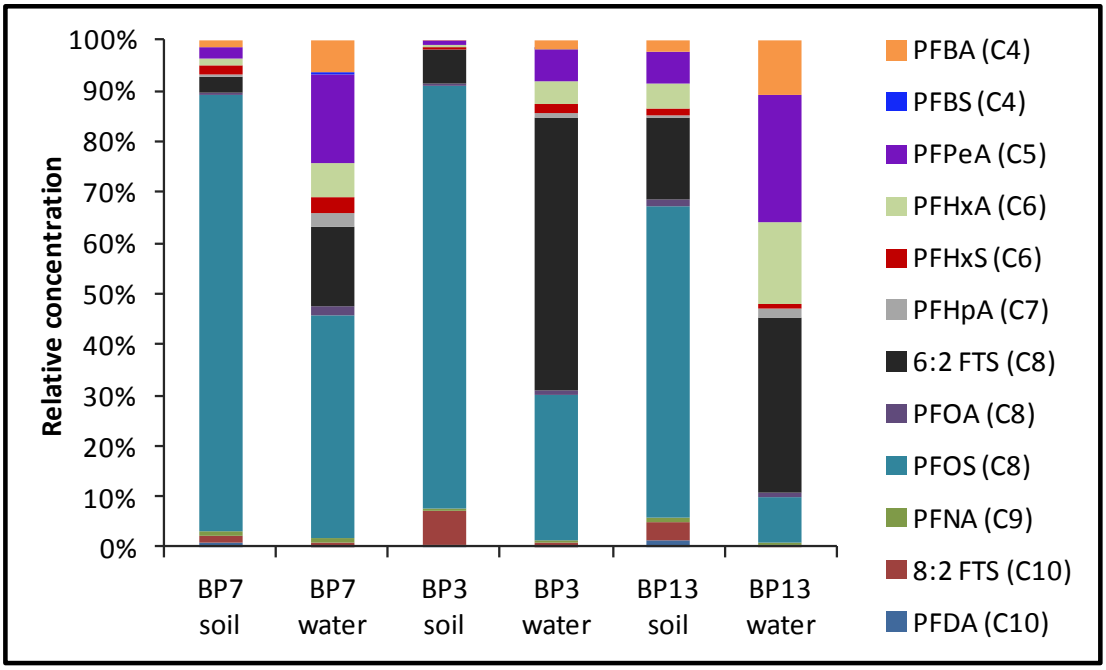


Figure 32: Relative average concentration distribution (%) of PFCs to the ΣPFC in soil and water from batch experiments with samples from Bergen.

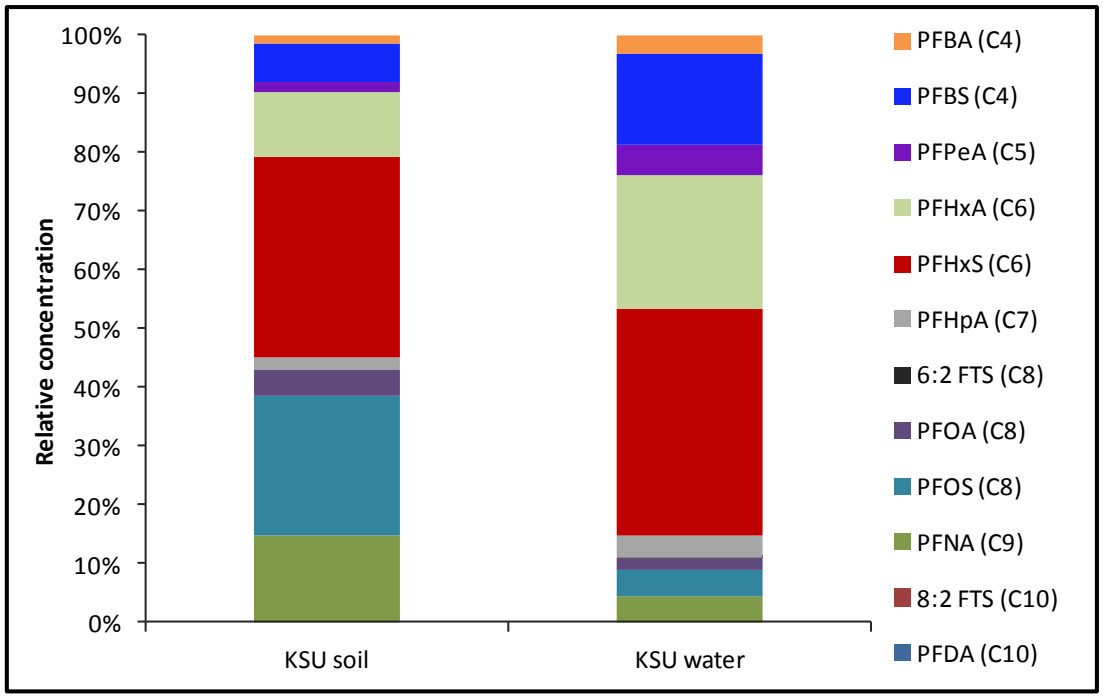


Figure 33: Relative average concentration distribution (%) of PFCs to the ΣPFC in soil and water from batch experiments with samples from Kristiansund.

5.2.3 Equilibruim partitioning coefficient (K_d) in relation to carbon chain length

K_d for the compounds quantified in samples from Kristiansand are plotted in ***Figure 34***. From the plot it can be seen that for sample KSA 30, with the lowest content of organic carbon (0.21 % TOC), there is no clear relationship between increasing K_d values and increasing carbon chain length of the compounds. In sample KSA30 the compound PFHxS (C6) has the highest calculated K_d, and is also the compound with the shortest carbon chain of the PFCs found in both soil and water at this site. 6:2 FTS (C8) and PFOS have almost similar K_d at this site (13.4 and 13.5 respectively) the compounds are both sulfonic. 6:2 FTS has a fluorinated carbon chain of six while PFOS has a fluorinated carbon chain length of eight. 8:2 FTS (C10), also with a fluorinated carbon chain of eight, has a slightly higher K_d (14.2) in this sample with very low TOC level. K_d values are increasing with increasing carbon chain length of the compounds in the two samples KSA 15 A and B, and the increase is steepest in sample KSA

15 A which has the highest total organic carbon content of these two sites (1.66 % TOC). In all Bergen samples (***Figure 35***) it is observed that PFOS and PFHxS have higher K_d values than the compounds of similar chain length. When excluding these two compounds, seven out of nine compounds show a positive correlation between K_d and carbon chain length in samples BP7 and BP3. In both samples PFBA (C4) has a relatively high K_d value (13.7 at BP3 and 15.1 at BP7), while 6:2 FTS (C8) has lower K_d than PFHpA (C7). K_d values for all compounds, except the higher values of PFOS and PFHxS, increase with increasing carbon chain length in sample BP13. The plot for the sample from Kristiansund (***Figure 36***) has nine calculated K_d values, and the association with carbon chain length is clear for six of them. The observations for K_d values of PFOS and PFHxS were similar to observations for samples from Bergen. In addition the acid PFPeA (C5) has lower K_d value compared to PFBA (C4).

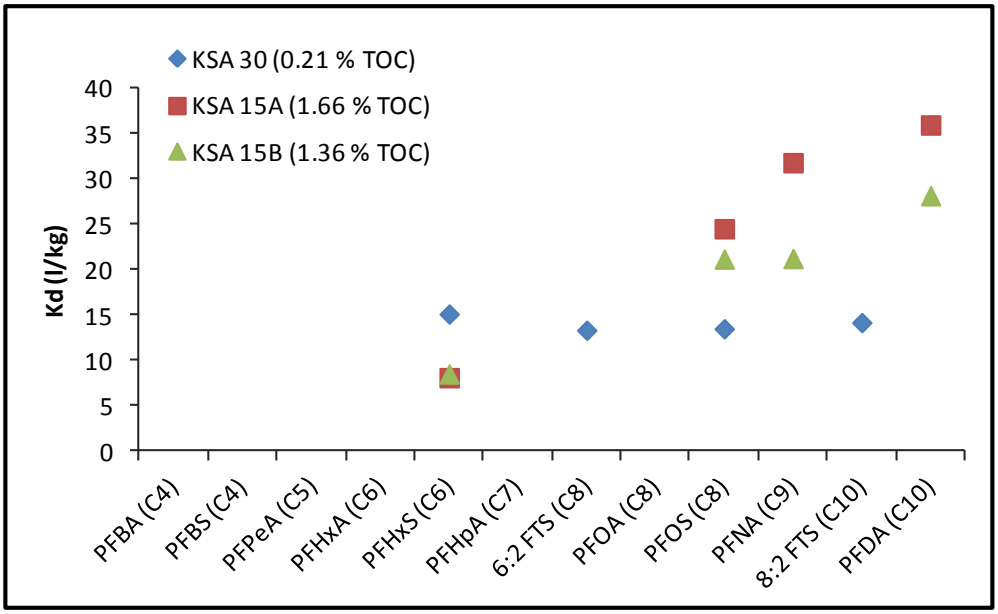


Figure 34: K_d values (l/kg) for the PFCs quantified in both soil and water samples from Kristiansand ordered after the carbon chain length of the compounds. Carbon chain lengths of the compounds increase from left to right.

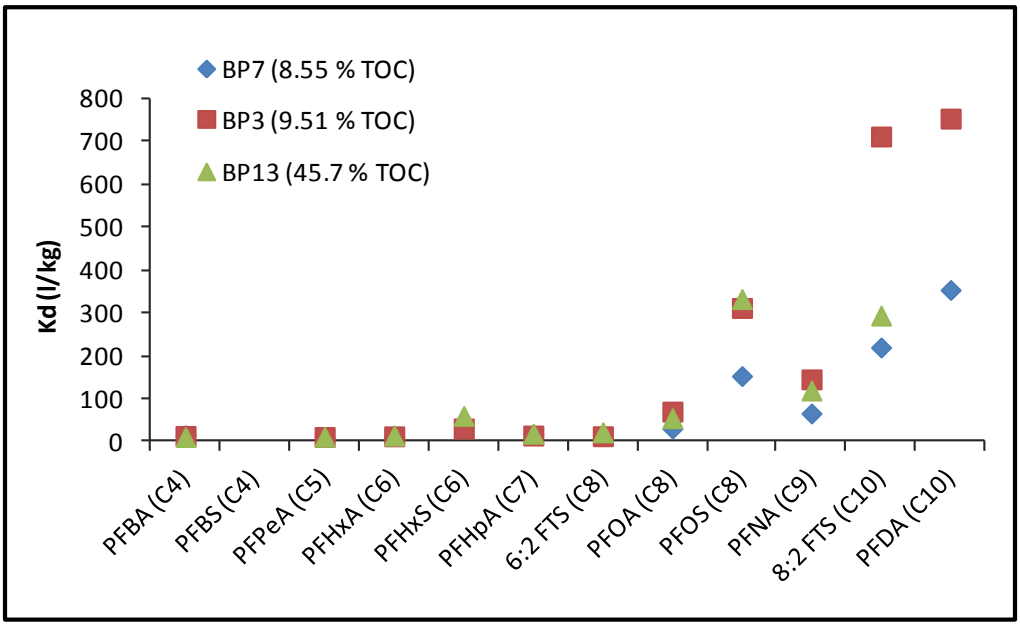


Figure 35: K_d values (l/kg) for the PFCs quantified in both soil and water samples from Bergen ordered after the carbon chain length of the compounds. Carbon chain lengths of the compounds increase from left to right.

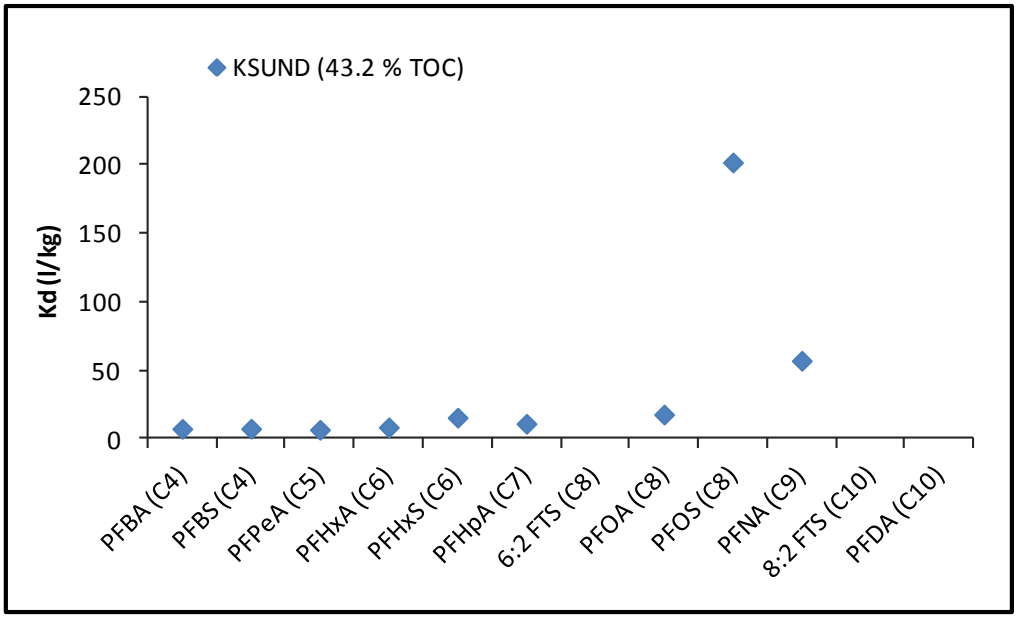


Figure 36: K_d values (l/kg) for the PFCs quantified in both soil and water samples from Kristiansund ordered after carbon chain length of the compounds. Carbon chain lengths of the compounds increase from left to right.

5.2.4 Equilibruim partitioning coefficient (K_d) in relation to TOC level

There was in general not found any clear linear correlations between log K_d and TOC in the soil, except for the three compounds PFDA, PFNA and PFOS (***Figure 37*** and ***Figure 38***). The two compounds PFNA and PFOS had calculated K_d values also for samples BP13 and Ksund, however, the positive linear relation only existed when these values were excluded from the plot. In soil from both samples BP13 and Ksund, the concentrations of PFNA and PFOS were lower and the TOC levels were higher. No calculated K_d values was excluded for PFDA.

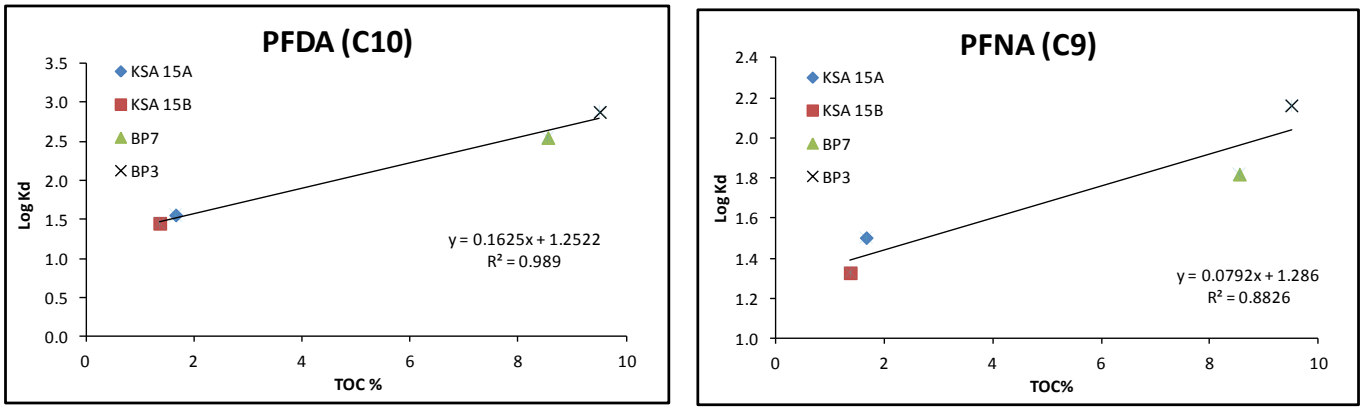


Figure 37: Positive linear correlation between log K_d and TOC (%) for PFDA (right) and PFNA (left). R-square values are displayed in the figures.

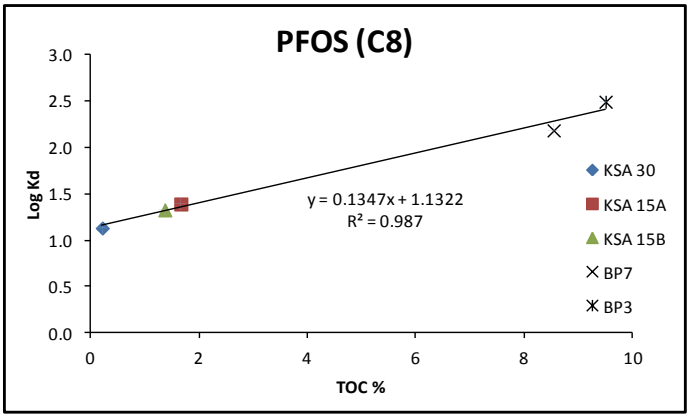


Figure 38: Positive linear correlation between log K_d and TOC (%) for PFOS. R-square values are displayed in the figures.

5.2.5 Relationship between total concentrations of each PFC and concentrations of the PFCs in water

There was in general not found any clear linear correlations between the PFC concentrations in soil and in water, except for the three acidic compounds, PFPeA, PFHxA, PFHpA (see ***Figure 39*** and ***Figure 40***). The plot for PFOS is shown as an example of no linear correlation (***Figure 40***).

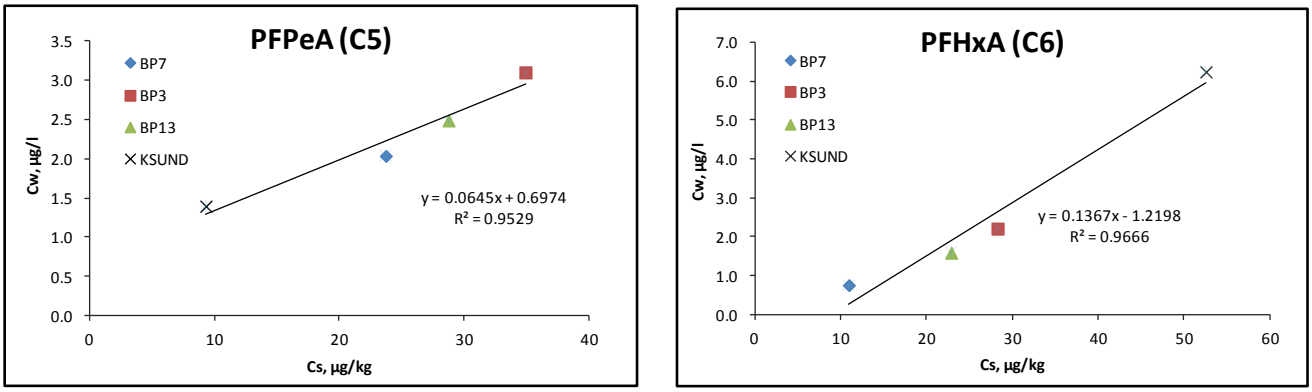


Figure 39: Concentration of PFCs in soil versus concentrations in water showed a positive linear relation for PFPeA (left) and PFHxA (right). R-square values are displayed in the figures.

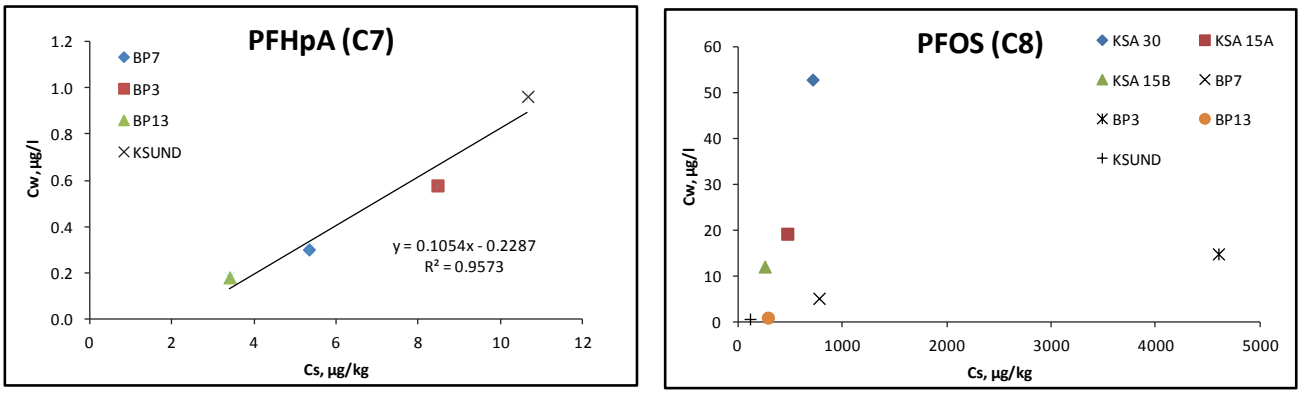


Figure 40: The plot of concentration in soil versus concentrations in water showed a positive linear relation for PFHpA (left), R-square value is displayed in the figure. The plot of concentration in soil versus concentrations in water showed no linear relation for PFOS (right).

5.2.6 Relationship between concentrations of calcium and PFC concentrations in water

It was explored if a possible relationship between PFC concentrations in the water samples and calcium concentrations in the soil samples existed. For the bulk of the compounds no relationship was observed. However, the long carbon chain compounds PFDA (C10), PFNA (C9), 8:2 FTS (C8) and PFOS (C8) had decreasing concentration in the water phase with increasing calcium concentrations in soil (see ***Figure 41***). The sample for Ksund was excluded in the plot for PFNA, as the concentration of the compound in leachate from this site was very much higher than for other sites (eight times higher than the second highest concentration in KSA15B).

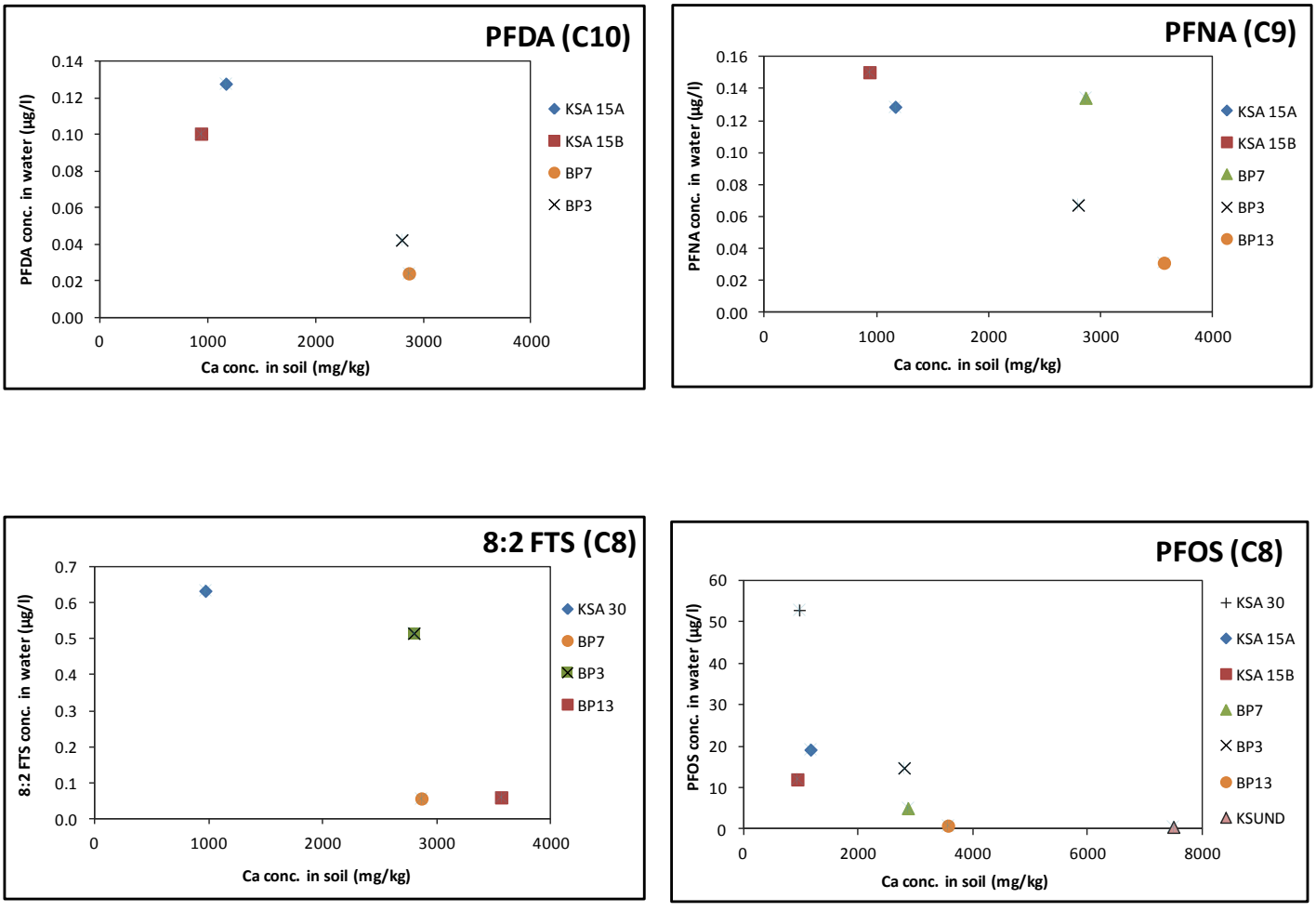


Figure 41: Concentration of PFDA (C10), PFNA (C9), 8:2 FTS (C8) and PFOS (C8) in water (µg/l) was decreasing with increasing calcium concentration in soil (µg/kg).

The two short carbon chain compounds PFHxA (C6) and PFBA (C4) showed the opposite behavior (***Figure 42***). The water concentrations of these compounds increased with increasing calcium concentrations in soil.

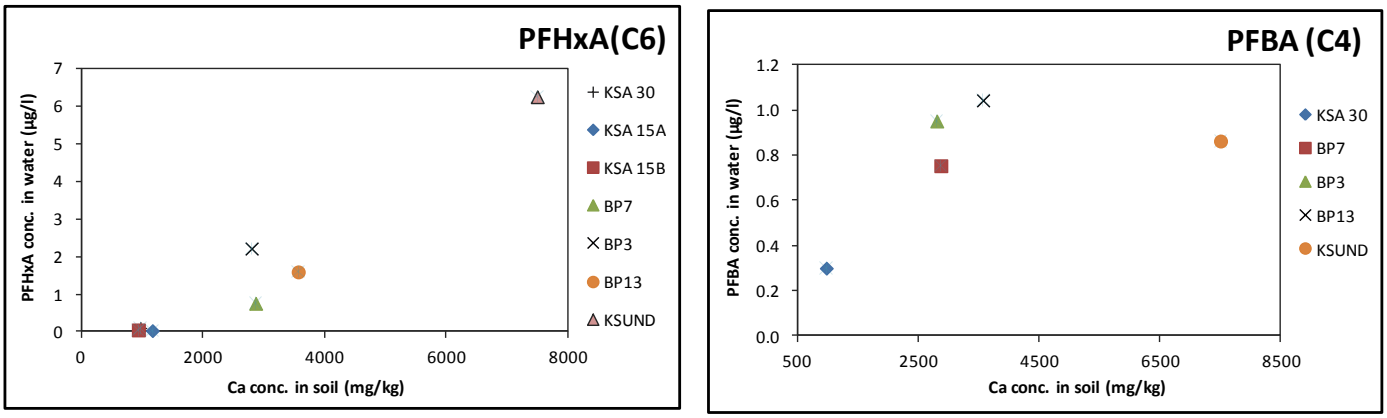


Figure 42: Concentration of PFHxA (C6) and PFBA (C4) in water (µg/l) was increasing with increasing calcium concentration in soil (µg/kg).

The calcium concentration in soil and in water samples from the different sites showed a positive linear relation (see ***Figure 43***), except for samples KSA 15 A and B. The two samples KSA 15 A and B had high concentrations of calcium in water and low calcium concentrations in soil.

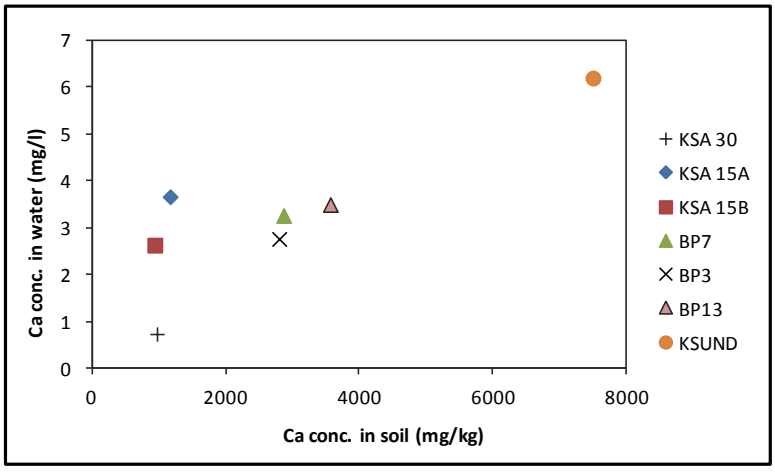


Figure 43: The concentration of calcium in water samples (µg/l) versus the concentration of calcium in soil samples (µg/kg) of batch experiments.

It was explored if a possible relation between PFC concentrations in the water samples and calcium concentrations in the water samples existed. This was not found for any of the compounds, except PFOS, 8:2 FTS and PFBA (see ***Figure 44***). For PFOS and 8:2 FTS there was a decreasing concentration in water with increasing concentration of calcium in the water. Highest concentrations of both compounds in water were in the sample KSA30, which had low concentrations of calcium in water and low calcium concentrations in soil. PFBA concentrations in water showed increasing concentrations in water with increasing calcium concentration in water.

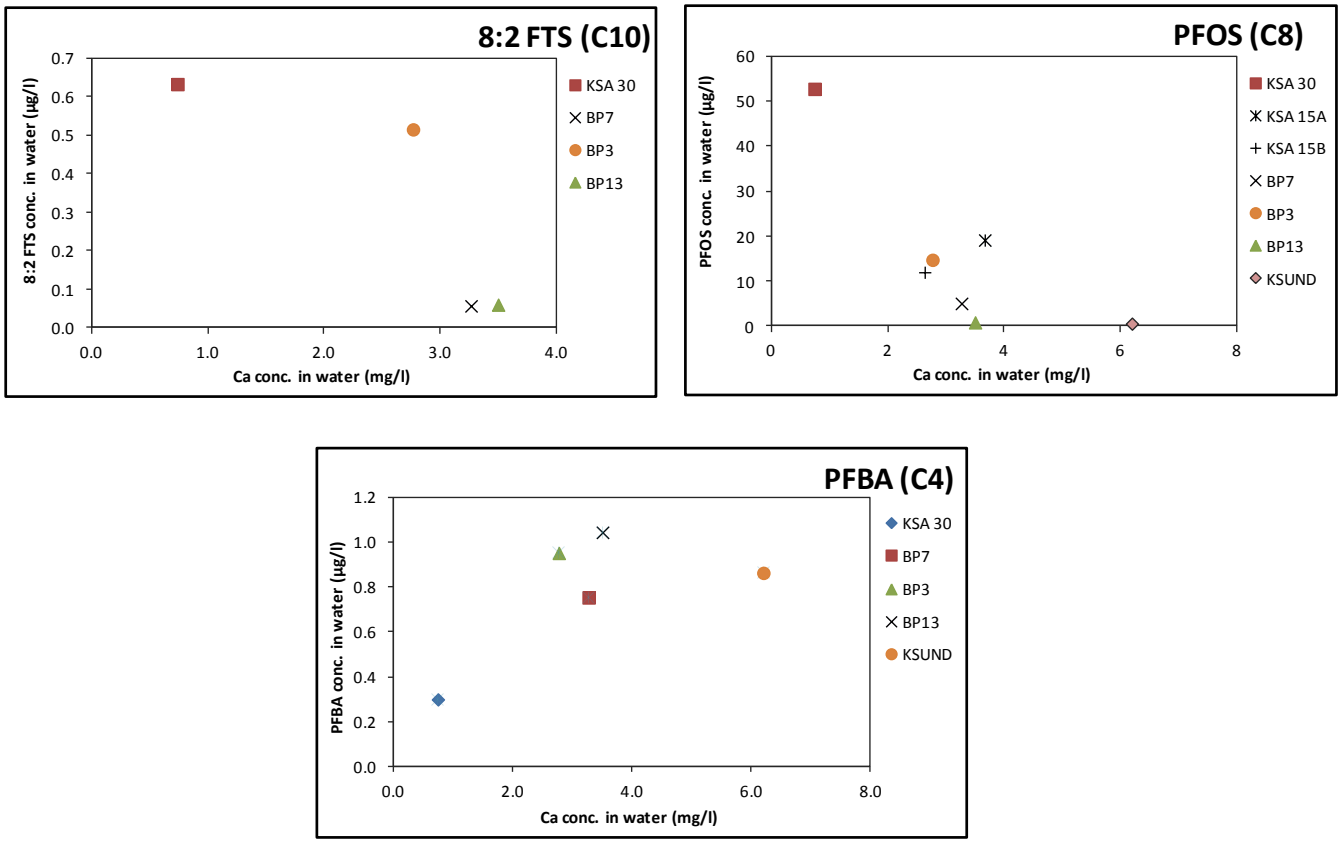


Figure 44: Concentration of 8:2 FTS (C10) and PFOS (C8) in water was decreasing with increasing calcium concentration in water (µg/l). PFBA (C4) in water (µg/l) was increasing with increasing calcium concentration in water (µg/l).

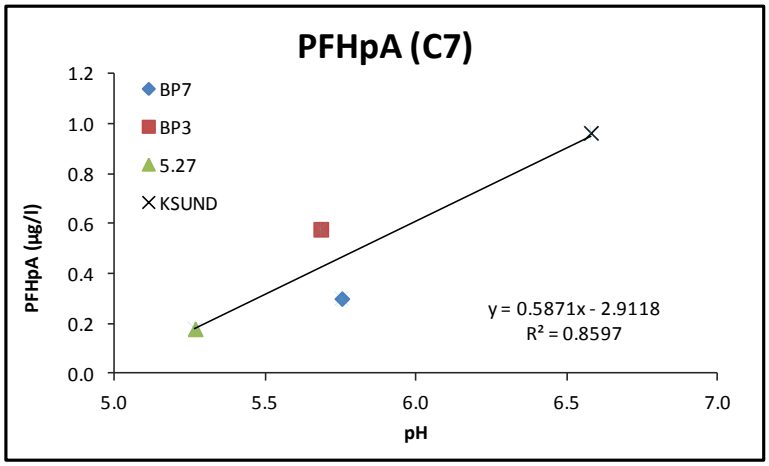


Figure 45 : Possible positvive linear correlation between the compound PFHpA and pH of the solution. R-square value is displayed in the figures.

In the batch experiment of this master thesis there was not attempted to change pH, and measurements show a narrow pH range for water samples of all 7 sites (5.27-6.84). There were in general not found correlations between PFC concentrations in the water samples and pH of the solution. However, a possible linear correlation between water concentration of PFHpA and pH was found (***Figure 45***). As the compound was present in only four of the water samples, and the samples had such a narrow pH range, this might not be a true correlation. It can therefore not be concluded that this correlation existed. Other explored correlations for the variations in concentrations of PFCs leached out of the different soil types were:

- There was found no linear correlation between the dissolved organic carbon (DOC) content in the water and the content of PFCs.
- For conductivity and water concentration of PFCs there was in general no linear correlations.

5.3 Column experiments

5.3.1 Concentrations of PFCs in leachate over time

The PFC concentrations over time in effluent water of columns from Kristiansand are shown in ***Figure 46*** (KSA30-A) and ***Figure 47*** (KSA30-B), PFOS is shown using a secondary axis. 46 porevolumes of water were flushed through each of these parallel columns in the period of the experiment, and the average water flow-velocity was 39 ml/h. When comparing the parallel columns, the compounds PFOS, 6:2 FTS, PFHxS and 8:2 FTS were found in leachate of both. However, the variations in concentration levels for the individual compounds over time were different for the columns. Average concentrations between the columns were not representative, and the concentrations of PFC in leachate are plotted separately for each column. The compound with highest concentrations in all the leachate samples from the parallel columns was PFOS, and the concentration of the compound decreased over time (170-4.94 µg/l for KSA30-A and 277-6.11 µg/l for KSA30-B). In the first samples of leachate, after 9 porevolumes, the concentration levels of PFOS from the parallel columns differed by a factor 1.6. After 18 porevolumes of water had flown through, the concentration levels of the compound were comparable between the parallel columns.

In leachate samples from KSA30-A the compound 6:2 FTS was measured in all samples, and the concentration level was decreasing over time. It can be noticed that the concentration of 6:2 FTS after 9 porevolumes was high (4.6 µg/l), compared to being < LOQ in the same water fraction for KSA30-B. The compounds PFHxS and PFPeA were found (< 1.16 µg/l) in the first sample of this column, while the compound 8:2 FTS was found in the two first samples (< 1.04 µg/l).

In leachate from KSA30-B 6:2 FTS was found in three samples (< 0.23 µg/l), all samples had lower concentrations than found in KSA30-A. The compounds PFHxS and 8:2 FTS were measured in two samples (< 0.17 µg/l). All three compounds were decreasing over time. The highest variety of compounds was in the sample taken after 46 porevolumes; this sample had low concentrations (< 0.07 µg/l) of 8 compounds other than PFOS.

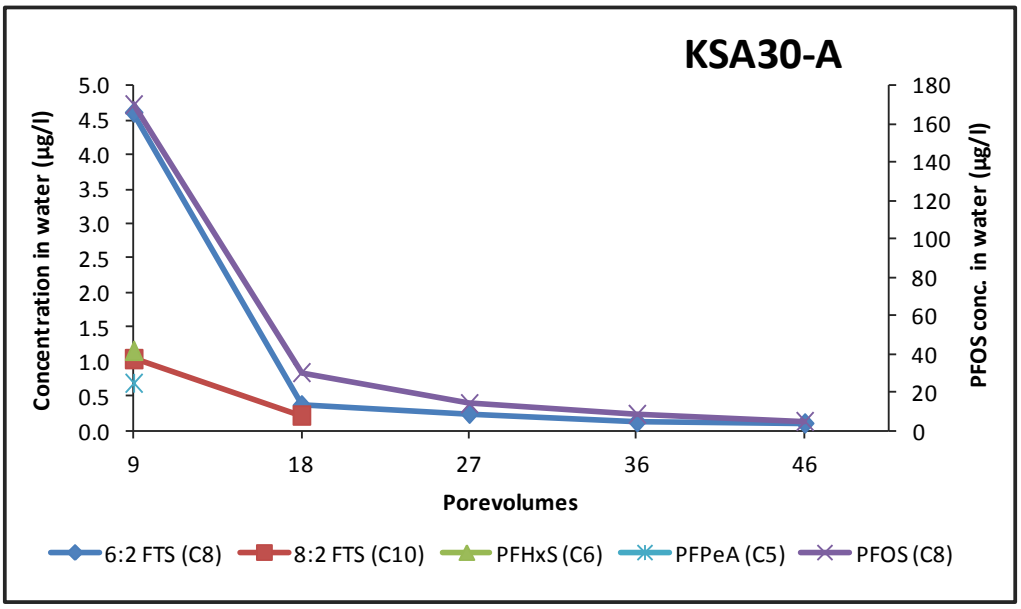


Figure 46: Concentrations of PFCs (µg/l) over time in effluent water from the column KSA30-A. PFOS is shown using a secondary axis.

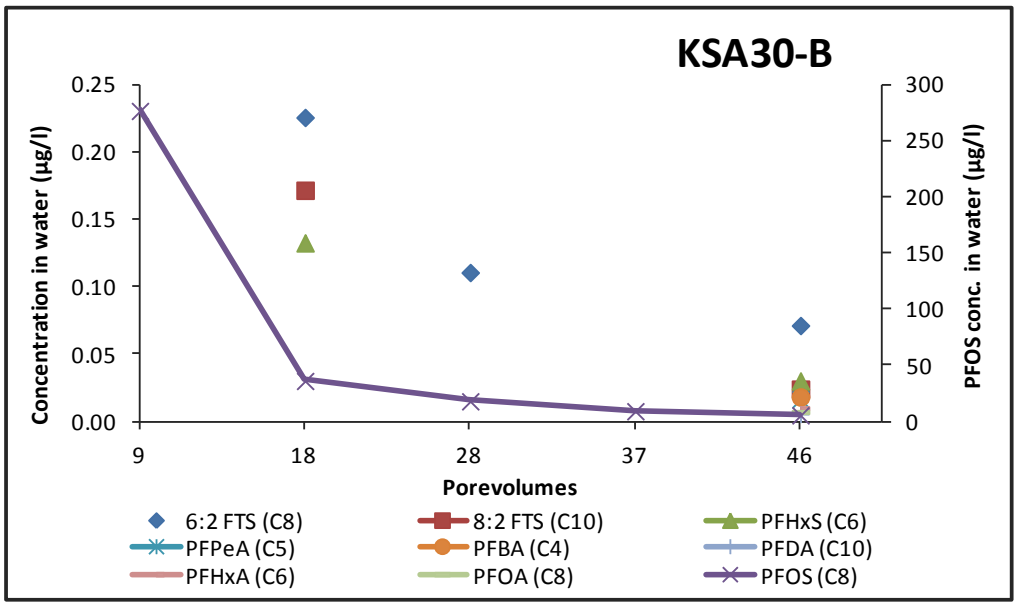


Figure 47: Concentrations of PFCs (µg/l) over time in effluent water from the column KSA30-B. PFOS is shown using a secondary axis.

Average PFC concentrations in effluent water of parallel columns from Bergen are shown in ***Figure 48*** and ***Figure 49***. The first figure show the PFC compounds with highest concentrations, and the second figure show the compounds with the lowest concentrations. Variations between the parallel columns are shown by minimum and maximum bars. A total of 4.4 and 4.5 porevolumes of water were flushed through BP3-A and BP3-B respectively, and the average water flow-velocities were 12.8 ml/h and 12.9 ml/h respectively. The compounds present in the samples of effluent water, and the variations in concentration levels for the individual compounds over time are very similar for the parallel columns. In the first water samples, after 0.9 porevolumes, 12 individual compounds were present in the leachate samples. In these samples the compound 6:2 FTS had the highest concentration (43 µg/l), and PFDA the lowest concentration (0.08 µg/l). In the last leachate samples of effluent water from BP3-A and BP3-B 10 and 11 compounds were present respectively. In these water samples PFOS had the highest concentration (27 µg/l), and PFPeA the lowest concentration (0.06 µg/l).

The majority of compounds; 6:2 FTS, PFPeA, PFHxA, PFBA, PFBS, PFHpA, and PFHxS had their highest concentration after 0.9 porevolumes, and the concentration levels thereafter decreased over time. PFDA and PFNA had their lowest concentrations after 0.9 porevolumes, while the levels increased after 1.8 porevolumes and stayed relatively constant throughout the experimental period. The two compounds 8:2 FTS and PFOA had their maximum concentration after 1.8 porevolumes, PFOA was then decreasing with time, while 8:2 FTS had a constant concentration level. The concentration of PFOS increased to its highest level after 3.6 porevolumes.

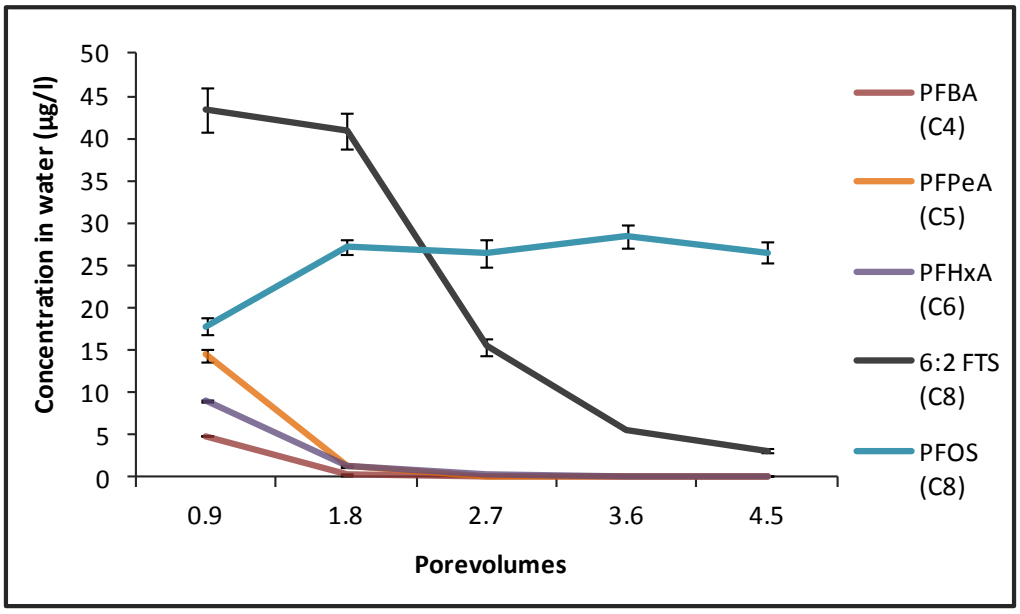


Figure 48: Concentrations (µg/l) of the PFC compounds PFBA, PFPeA, PFHxA, 6:2 FTS and PFOS over time in effluent water from the parallel columns from Bergen (average of BP3-A and BP3-B). The error bars show the max and min concentration in each sample of leachate.

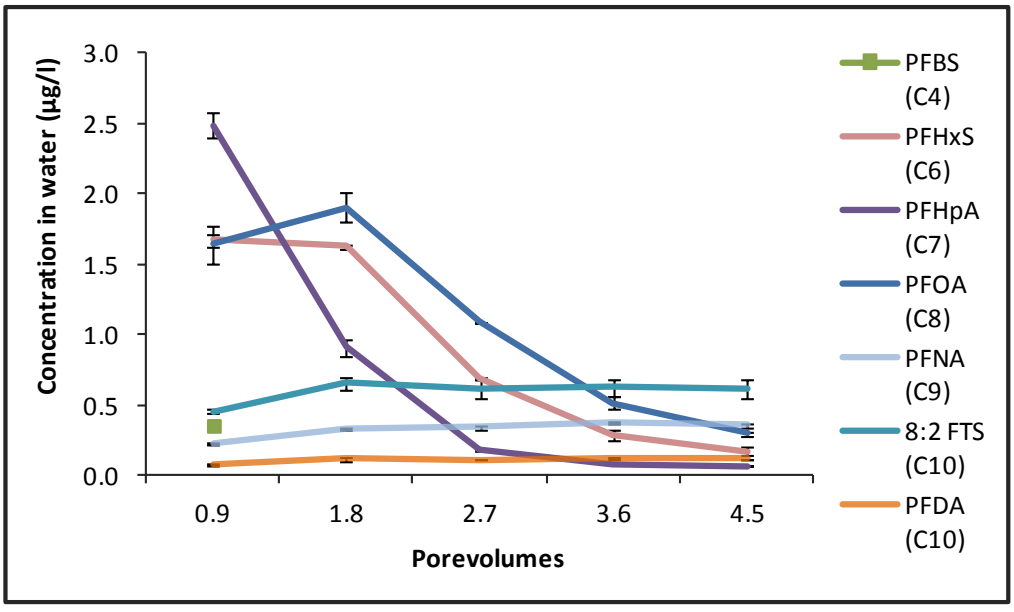


Figure 49: Concentrations (µg/l) of the PFC compounds PFBS, PFHxS, PFHpA,PFOA, PFNA, 8:2 FTS and PFDA over time in effluent water from the parallel columns from Bergen (average of BP3-A and BP3-B). The error bars show the max and min concentration in each sample of leachate.

The PFC concentrations in effluent water samples of columns from Kristiansund are shown in ***Figure 50*** and ***Figure 51***. The first figure show the PFC compounds with highest concentrations, and the second figure show the compounds with the lowest concentrations. Variations between the parallel columns are shown by minimum and maximum bars. A total of 1.1 and 1.3 porevolumes of water was flushed through the columns KSU-A and KSU-B respectively, and the average water flow-velocity was 4.3 ml/h and 3.3 ml/h respectively. When comparing the leachate samples of these parallel columns, a total of 9 compounds were present in all the samples over time, these were the same compounds for both columns. In the first leachate samples the compound PFHxS had the highest concentration (14 µg/l), and PFOS the lowest concentration (0.67 µg/l). In the last water samples of effluent PFHxS still had the highest concentration (12 µg/l), and PFBA the lowest concentration (0.29 µg/l).

6 compounds show the same variations in concentration levels over time in leacahte from the parallel columns. PFBS, PFHxA, PFBA, PFHpA, and PFPeA were decreasing with time, while PFOS was increasing with time. The tree other compounds PFHxS, PFOA and PFNA behaved differently over time in effluent water of the parallel columns, and the error bars in the figures are larger. In KSU-A the compounds PFHxS and PFOA had the highest concentration in the second sample, and then decreased after 1.1 porevolumes. In KSU-B the same compounds increased steadily with time, having their lowest concentration in the first sample, and highest concentrations after 1.3 porevolumes. The compound PFNA increased over time in effluent water from both columns, however, the increase was steeper for KSU-A than for KSU-B. The concentrations of PFCs in leachate samples of column experiments can be found in appendix C.

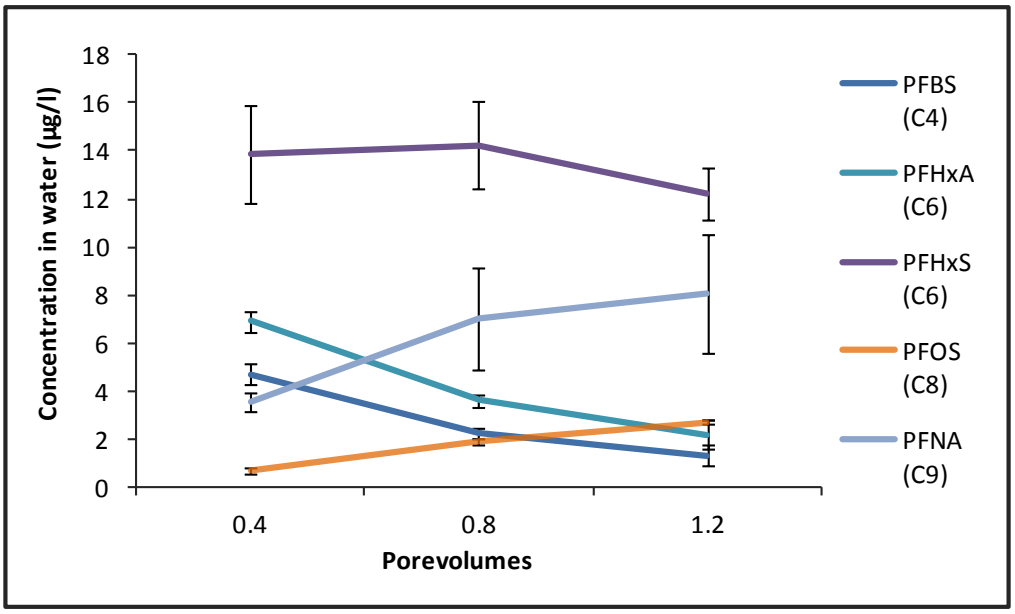


Figure 50: Concentrations (µg/l) of the PFC compounds PFBS, PFHxA, PFHxS, PFOS and PFNA over time in effluent water from the parallel columns from Kristiansund (average of KSU-A and KSU-B). The error bars show the max and min concentration in each sample of leachate.

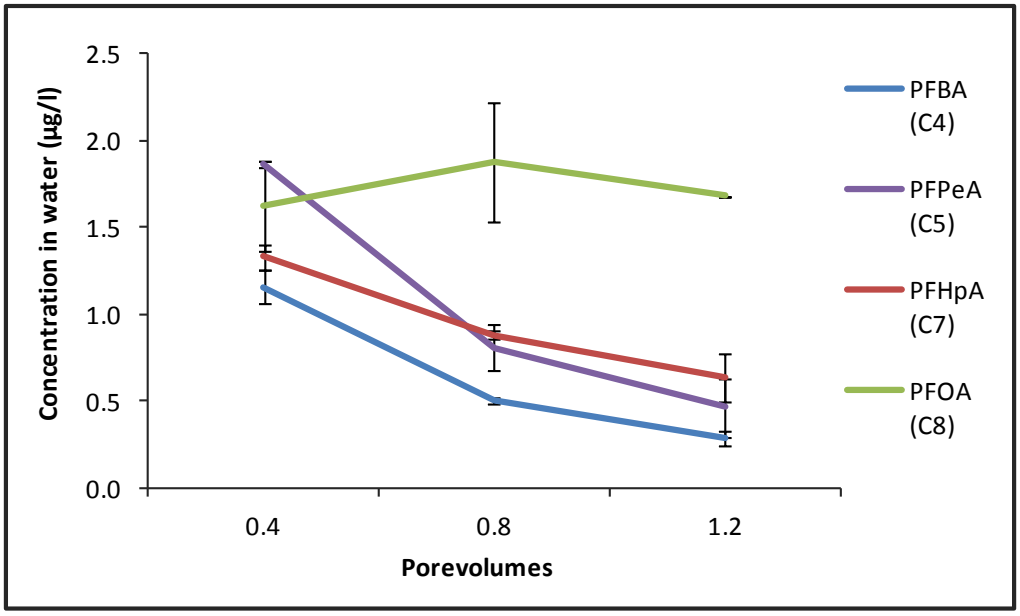


Figure 51: Concentrations (µg/l) of the PFC compounds PFBA, PFPeA, PFHpA and PFOA over time in effluent water from the parallel columns from Kristiansund (average of KSU-A and KSU-B). The error bars show the max and min concentration in each sample of leachate.

5.3.2 Sum of PFC concentrations in leachate over time

The ΣPFC concentrations in leachate (µg/l) from the columns is shown in ***Figure 52***, ***Figure 53*** and ***Figure 54***. In leachate of columns from Kristiansand, the highest decrease in ΣPFCs was in the samples after 18 porevolumes. The factor of decrease was as high as eight for the sample of leachate after 18 porevolumes relative to the sample after 9 porevolumes. In samples of leachate from 27 to 46 porevolumes the decrease in the ΣPFCs flattens out to an average factor of 1.8 for both columns. The figure shows that the total decrease is due to decreasing PFOS concentration. In effluent water of columns from Bergen there was a relatively steady decrease in the ΣPFCs over time. The average factor of decrease for each sample over time of both columns was 1.3, and the highest decrease was for porevolume 2.7 relative to porevolume 1.8. It is clear from the figure that the decrease in ΣPFC concentrations over time is exclusively caused by lower concentrations of shorter carbon chain compounds (< C8), and the compound 6:2 FTS. In leachate from the parallel columns from Kristiansund, the average factor of decrease for each sample over time in the experiment was 1.1. As the concentration of longer carbon chain compounds (> C8) is increasing over time, the total decrease of PFCs is caused by lower concentrations of shorter carbon chain compounds (< C8).

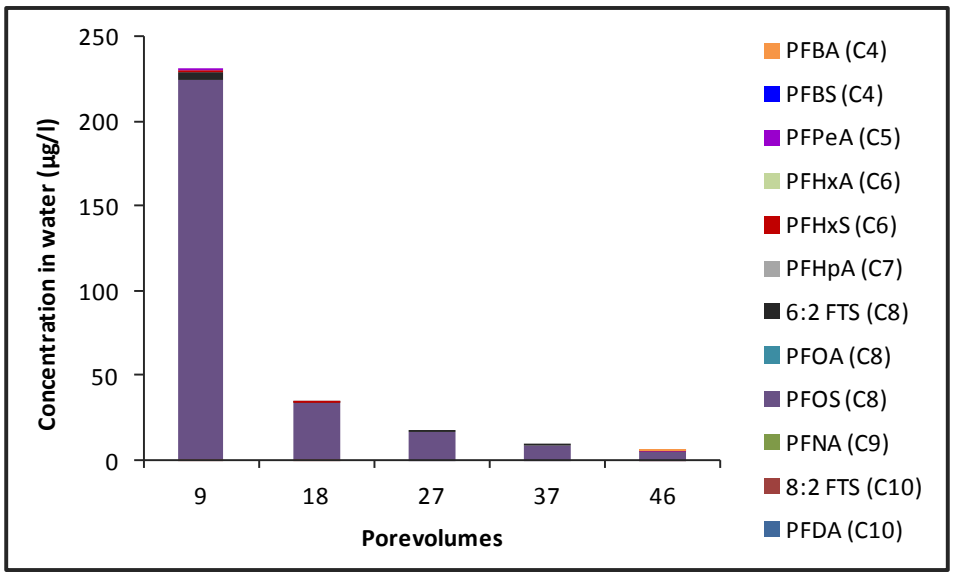


Figure 52: The ΣPFC concentrations in leachate (µg/l) of the columns from Kristiansand over time, organized according to increasing carbon chain length of the individual PFCs (average of columns KSA30-A and KSA30-B).

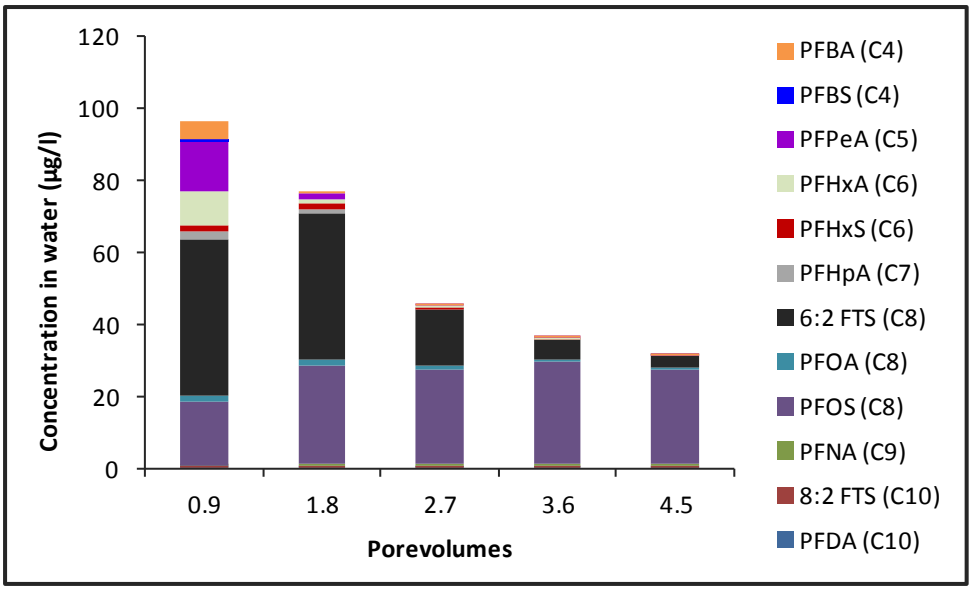


Figure 53: The ΣPFC concentrations in leachate (µg/l) of the columns from Bergen over time, organized according to increasing carbon chain length of the individual PFCs (average of columns BP3-A and BP3-B).

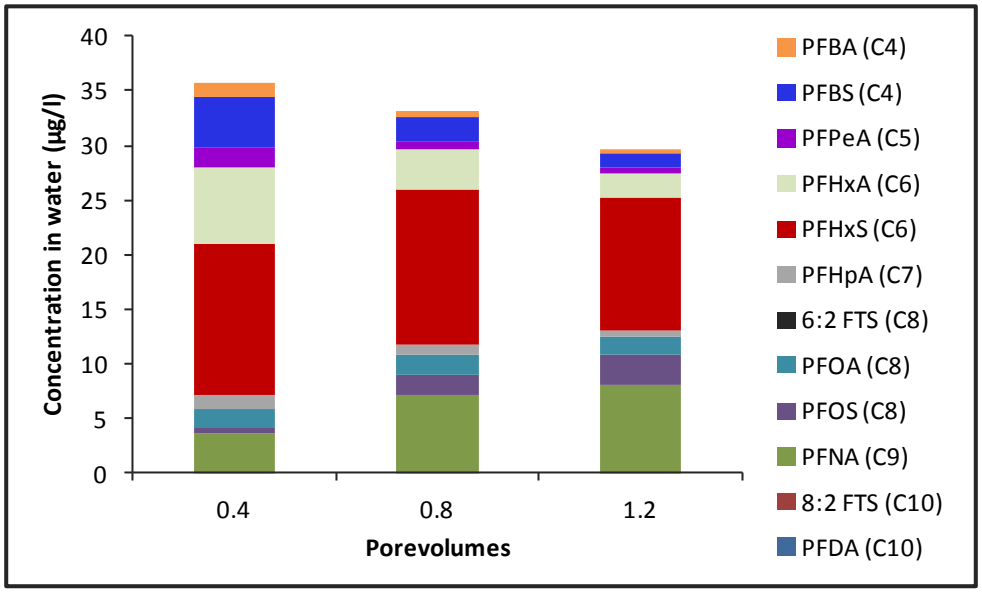


Figure 54: The ΣPFC concentrations in leachate (µg/l) of the columns from Kristiansund over time, organized according to increasing carbon chain length of the individual PFCs (average of columns KSU-A and KSU-B).

5.3.3 Relative concentration distribution of PFCs in leachate over time

The average relative distribution (%) of PFCs to the ΣPFC in leachate from the columns over time is shown in ***Figure 55***, ***Figure 56*** and ***Figure 57***. PFOS was the main component in all samples from Kristiansand. In water from KSA30-A the highest variety of compounds were in the sample taken after 9 porevolumes with five compounds found, while for KSA30-B the highest variety was in the sample taken after 46 porevolumes, with nine compounds found. The dominating components in all samples of leachate of columns from Bergen were 6:2 FTS and PFOS. The compound 6:2 FTS (C8) and the shorter carbon chain compounds (< C8) are dominant in leachate samples taken after 0.9 and 1.8 porevolumes. In the samples of water from 27 to 46 porevolumes, PFOS and the longer carbon chain compounds become increasingly dominant. In leachate of columns from Kristiansund, PFHxS, PFNA and PFHxA were the dominating compounds. The shorter carbon chain compounds (< C8) have a decreasing relative contribution over time, and the longer carbon chain compounds (≥ C8) show an increase in relative contribution over time. For PFOA (C8) there is no clear trend in the relative contribution over time. The shorter carbon chain compounds are dominant in all samples of leachate of columns from Kristiansund.

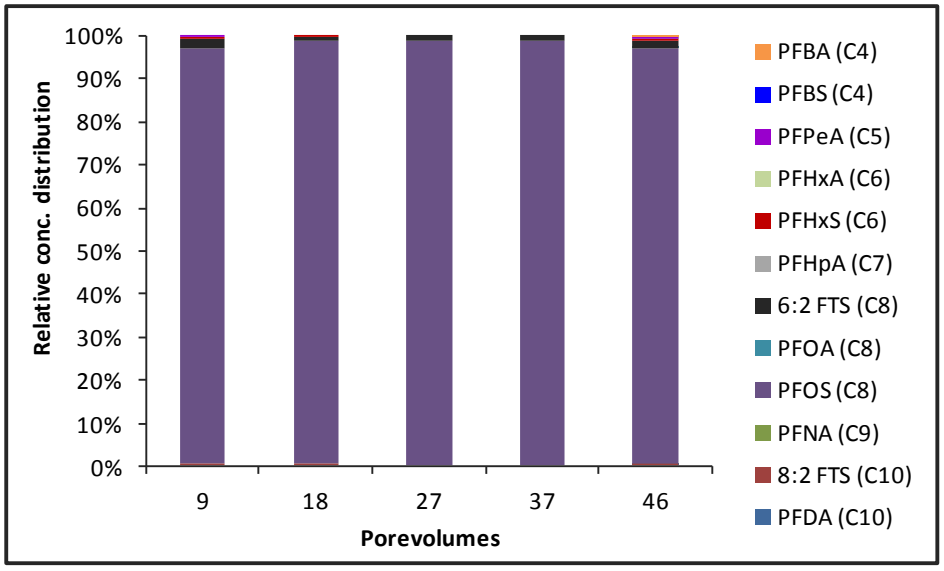


Figure 55: The relative concentration distribution (%) of PFCs to the ΣPFC in leachate (µg/l) of the columns from Kristiansand over time, organized according to increasing carbon chain length (average of columns KSA30-A and KSA30-B).

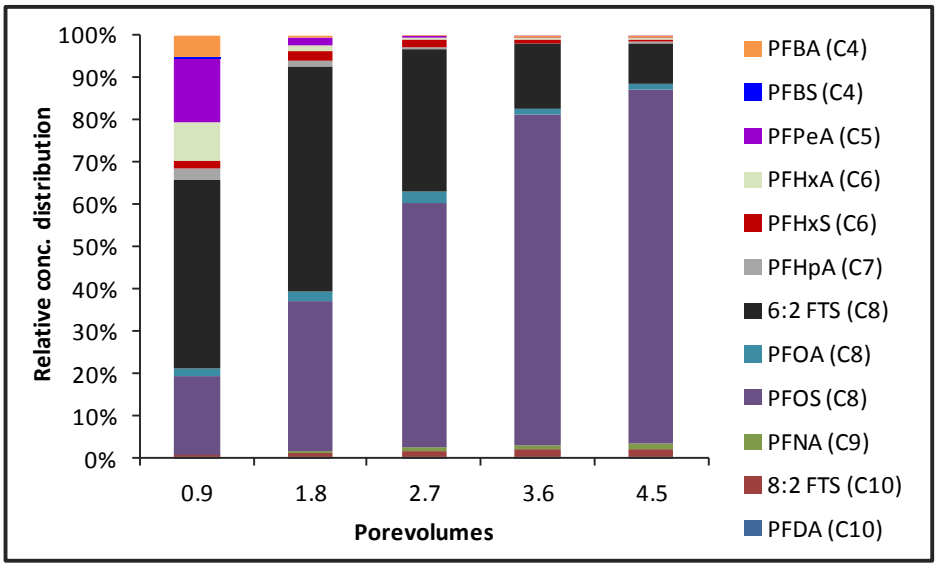


Figure 56: The relative concentration distribution (%) of PFCs to the ΣPFC in leachate (µg/l) of the columns from Bergen over time, organized according to increasing carbon chain length (average of columns BP3-A and BP3-B).

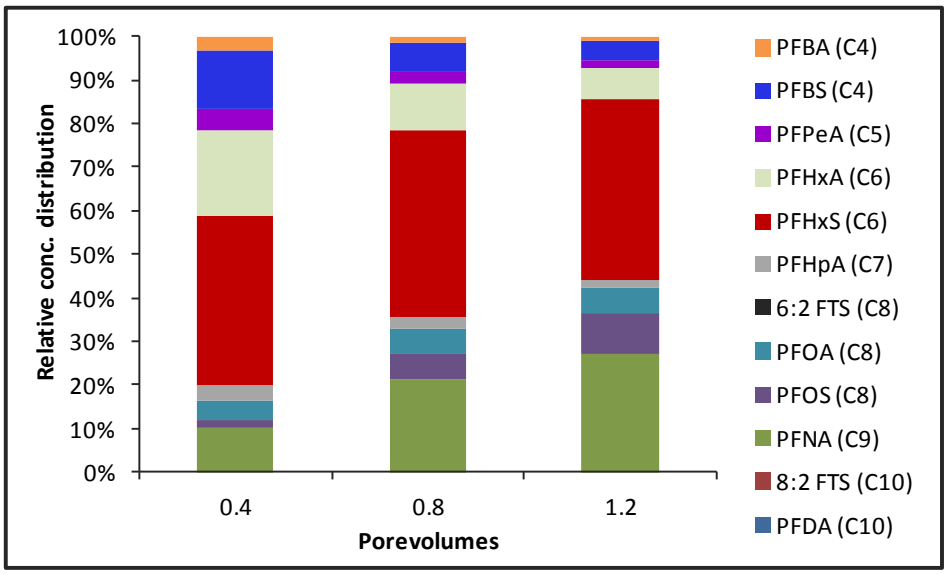


Figure 57: The relative concentration distribution (%) of PFCs to the ΣPFC in leachate (µg/l) of the columns from Kristiansund over time, organized according to increasing carbon chain length (average of columns KSU-A and KSU-B).

5.3.4 Percent of individual PFCs leached out of soil

A mass balance for the 12 individual compounds was calculated as for the batch experiment. From this the percent of the individual compounds leached out from the initial amount in soil was found. The accumulation of the individual PFCs (%) in leachate over time for columns from Kristiansand are shown in ***Figure 58*** and ***Figure 59***. The amount leached out of soil could only be calculated for the compounds over the limit of quantification in soil. In soil from KSA30 this was the four sulfonic compounds 6:2 FTS, PFOS, PFHxS and 8:2 FTS. For the compounds PFOS and 6:2 FTS the accumulation over time are very different for the parallel columns, and the results for each column are plotted separately. For column KSA30-A the calculations show 170 % leaching of 6:2 FTS in the first sample, and after 46 porevolumes the total accumulated leaching reached 201 %. The leaching of PFOS reaches almost 60 % of the initial amount in soil of column KSA30-A. The total accumulated leaching of PFHxS and 8:2 FTS from soil were 41 % and 25 % respectively. For column KSA30-B the total accumulation of 6:2 FTS was 18.6 % of the initial amount in soil, and the total accumulated leaching of PFOS was 108 %. The compounds PFHxS and 8:2 FTS had a total accumulated leaching of and 7.1 % and 4.8 % respectively.

The average accumulation of PFCs (%) in leachate of parallel columns from Bergen over time is shown in ***Figure 60*** and ***Figure 61***. The first figure show the PFC compounds with highest total accumulation, and the second figure show the compounds with the lowest total accumulation. Variations between the parallel columns are shown by minimum and maximum bars. In soil form Bergen the amount could be calculated for 11 compounds, as only the compound PFBS was under LOQ. The accumulation of the individual compounds in leachate of the parallel columns showed very similar trends over time, and the largest variations between columns were for PFBA and PFPeA. However, among the 11 compounds there were large variations in the amount that leached out of the soil. PFPeA is the compound with highest total leaching of all compounds (92 %), while 8:2 FTS is the compound with lowest total leaching (1.62 %). For the compounds PFBA, PFHxA, PFHpA, 6:2 FTS and PFOA more than 50 % of the total amount in soil leached out during the experimental period. The compounds PFHxS, PFOS, PFDA and PFNA leached out in the range 3.4 % to 33 % of the total amount.

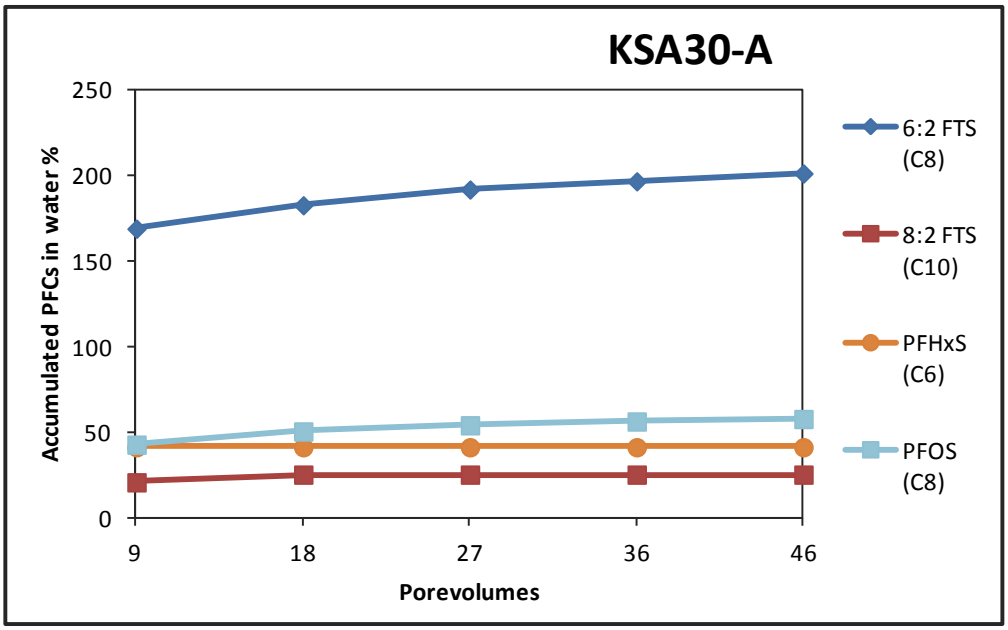


Figure 58: Accumulated PFCs (%) over time in the effluent water of column KSA30-A.

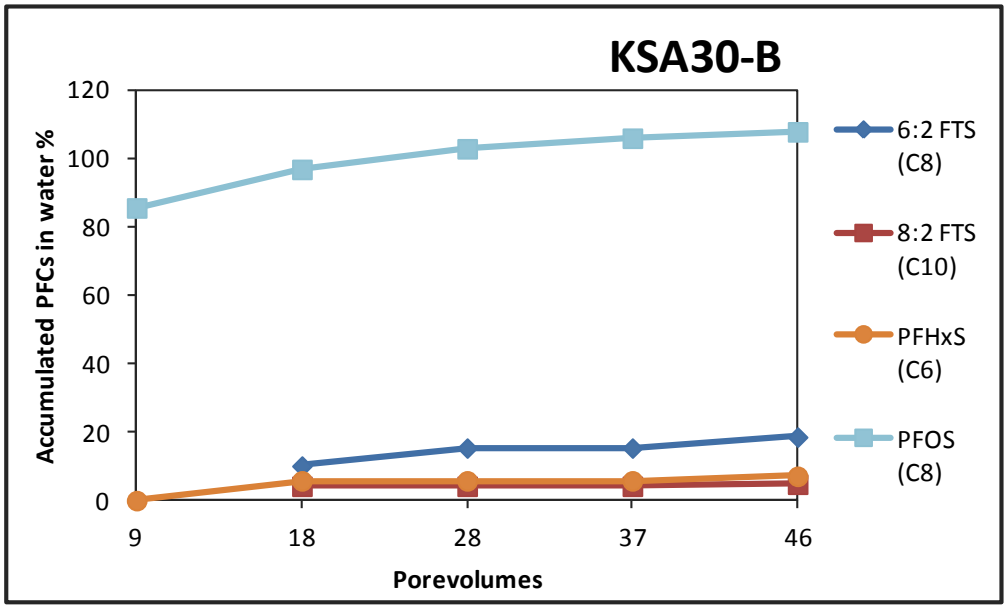


Figure 59: Accumulated PFCs (%) over time in the effluent water of column KSA30-B.

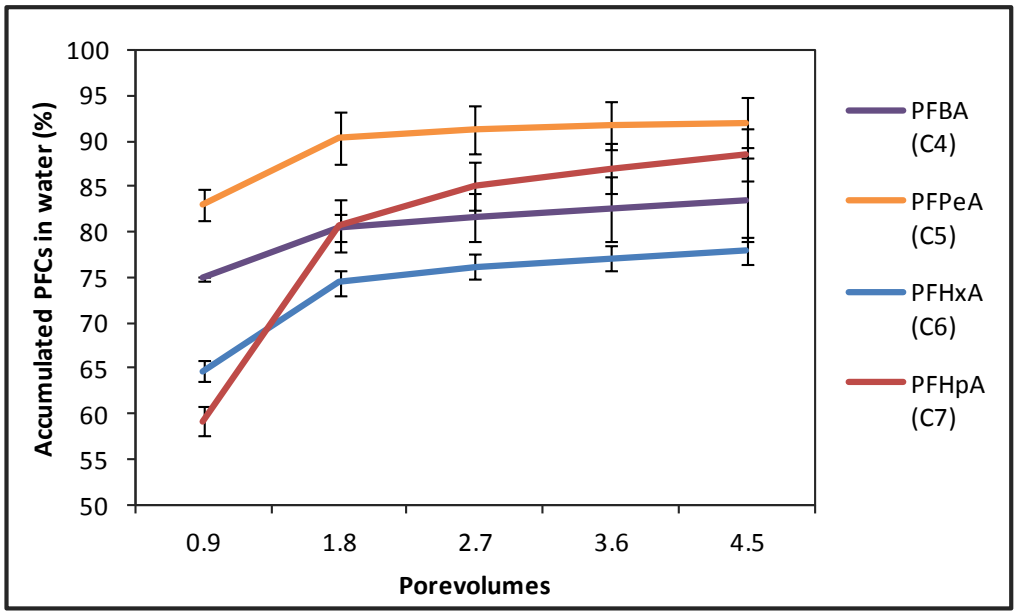


Figure 60: Accumulation (%) of PFC compounds PFBA, PFPeA, PFHxA and PFHpA over time in the effluent water of columns from Bergen (average of BP3-A and BP3-B). The error bars show the max and min concentration in each sample of leachate.

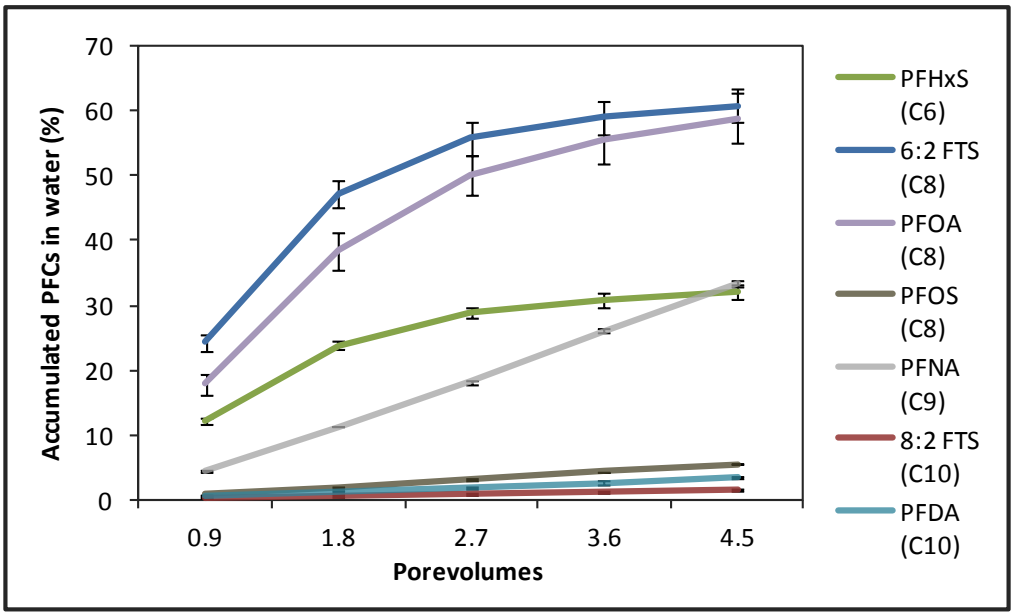


Figure 61: Accumulation (%) of PFC compounds PFHxS, 6:2 FTS, PFOA, PFOS, PFNA, 8:2 FTS, and PFDA over time in the effluent water of columns from Bergen (average of BP3-A and BP3-B). The error bars show the max and min concentration in each sample of leachate.

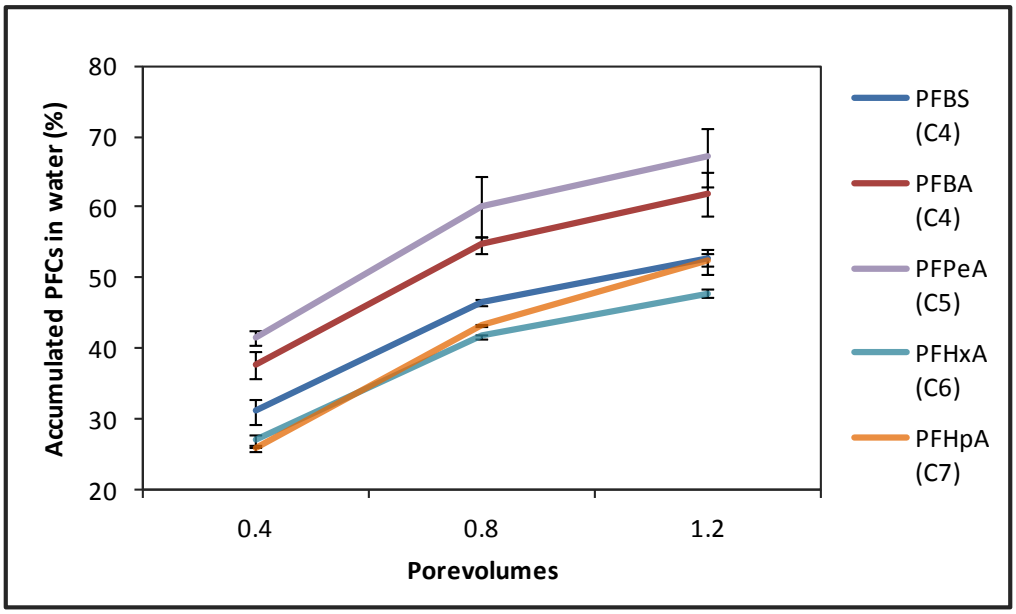


Figure 62: Accumulation (%) of PFC compounds PFBS, PFBA, PFPeA, PFHxA and PFHpA over time in the effluent water of columns from Kristiansund (average of KSU-A and KSU-B). The error bars show the max and min concentration in each sample of leachate.

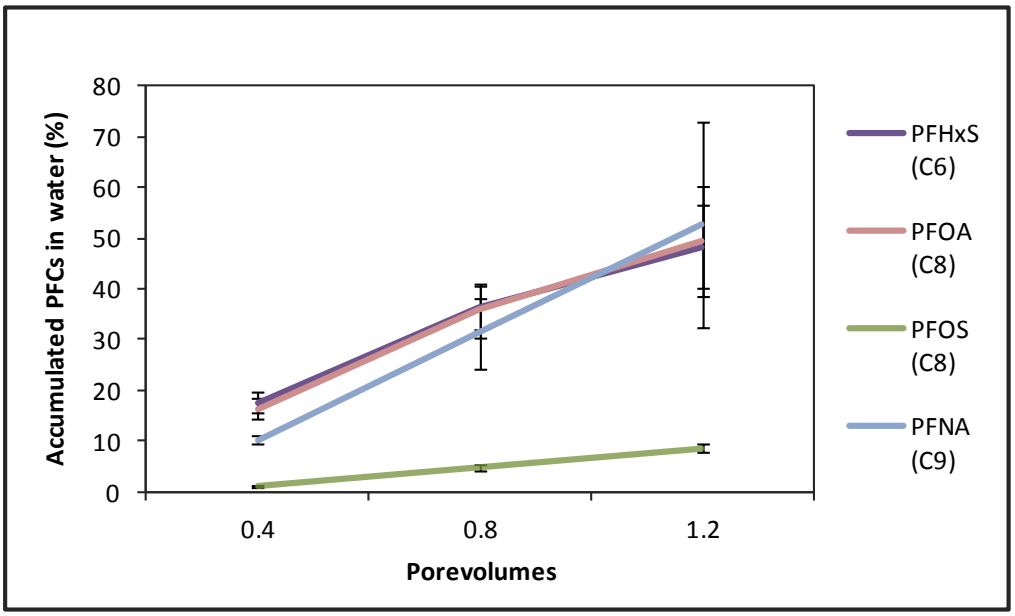


Figure 63: Accumulation (%) of PFC compounds PFHxS, PFOA, PFOS and PFNA over time in the effluent water of columns from Kristiansund (average of KSU-A and KSU-B). The error bars show the max and min concentration in each sample of leachate.

The accumulation of PFCs (%) in leachate of columns from Kristiansund over time is shown in ***Figure 62*** and ***Figure 63***. The first figure show the PFC compounds with highest total accumulation, and the second figure show the compounds with the lowest total accumulation. Variations between the parallel columns are shown by minimum and maximum bars. In soil samples from Kristiansund the amount could be calculated for nine individual compounds. As seen from the error bars, the highest variability between columns was for the compounds PFNA, PFOA and PFHxS in the sample taken after 1.2 porevolumes. The compound with highest total accumulation in lechate was PFPeA (67 %), and PFOS had the lowest (8.7 %). For compounds PFBS, PFBA, PFPeA, PFHxA and PFHpA the total accumulation in lechate was within 48 % to 67 % of the amount in soil. For compounds PFHxS, PFOA, PFNA and PFOS the total accumulation in leachate were from 8.7 % to 53 % of the amount in soil.

6. Discussion

6.1 Soil characterization

6.1.1 Total PFC concentrations in soil

Since the soil samples were collected from four different fire fighting training stations at three airports, there are many different factors that may explain the measured soil concentrations; for instance the types of foam products used, the time since usage, soil types, TOC level, drainage at the site and depth of sampling. At Kristiansand airport the sample KSA30, from the fire fighting training stations used from 1985 to 2008, had the highest ΣPFC concentrations. The samples from the site KSA15, used before 1985, had higher ΣPFC concentrations in the upper soil (50 cm depth), than at depth (80-85 cm) where the total concentrations were low. A higher total concentration of PFCs was expected at the newest of the fire fighting training stations, as the latest use of AFFF were in 2008. At the oldest fire fighting training station the release of AFFF to soil stopped after 1985, and the leaching of PFCs from the site potentially has been going on for more than 27 years.

At Bergen airport there was large variations in the ΣPFCs in soil. Sample BP3 and BP7 had the highest total concentrations of all the samples from the three airports. A high ΣPFC concentration was expected in the sample BP3, as the sampling site was located in the area where the airport fire personnel aim the fire fighting foam during training, as described in section 3.1.1. The sample BP13 had the lowest total concentration of the samples from the sites at Bergen, and was on the opposite side of the training platform than BP3 and BP7. Possibly in the “shadow” of where the firefighting foam was aimed during training. The new fire fighting training station at Bergen has been used from 1995, and has a very thin soil layer covering the bedrock in the area around the platform combined with a relatively high TOC level. These are factors that are thought to contribute significantly to the elevated PFC concentrations in soil at this fire fighting training station.

The ΣPFC concentrations in natural peat from the old training station used before 2004 at Kristiansund was among the lowest of all the samples from the three airports. At this site the soil material was collected at the largest depth of all the samples, 200-250 cm below the surface, and consisted of degrading roots and decomposed organic material. Heavily PFC polluted masses in the central part of the training station had been replaced after year 2002, which likely would have reduced the leakage to larger depths were the soil samples was collected.

6.1.2 Relative concentrations of PFCs in soil

There are strong variations in the relative content of the various PFCs to the ΣPFC in the soil samples. This might be a result of the contamination history of the studied sites. In soil samples from Kristiansand with relatively equal levels of TOC, it is interesting that there was a difference in the composition of PFCs at the two sampled fire fighting training stations. The compounds 6:2 FTS, and 8:2 FTS, were found in sample KSA30 from the fire fighting training site used from 1985-2008. The compounds 6:2 FTS and 8:2 FTS are typically found in more recently polluted areas, as they were used as replacement for PFOS in fire fighting foam used from 2001(Klif, 2010; Øvstedal, 2012a). The soil samples KSA 15 A and B, from the fire fighting training station used before 1985, had the two long carbon chained acids PFNA and PFDA. Even though the TOC levels are relatively equal in the three soil samples, the slightly lower TOC in sample KSA30 might be why PFNA and PFDA are not found at the most recently used fire fighting training station. The high relative contribution of PFOS in all soil samples from Kristiansand, are likely resulting from AFFFs that have been used at these training stations were containing PFOS most of the time the stations was active.

Soil samples from Bergen have the greatest variety of PFCs with concentrations over quantification limit for all compounds analyzed, except PFBS. The compounds 6:2 FTS and 8:2 FTS, related to the use of newer AFFF, were found in all Bergen samples. Klif (2010) also found relatively high concentrations of 6:2 FTS in soil close to the platform of the new fire training station of Bergen airport, this was explained as resulting from recent use of the compound.

Soil samples from Kristiansund also have high variety of compounds, but a quite different relative concentration distribution than found at Bergen. All compounds analyzed for were quantified at this site, except 6:2 FTS, 8:2 FTS and PFDA. The fire fighting training station at Kristiansund was used until 2004, and fire fighting foam containing 6:2 FTS or 8:2 FTS has also been used at this site. 6.2 FTS was detected at a low concentration (0.068 µg/l) in one water sample of the batch experiments, indicating that it is present under LOQ in soil. The fact that 6:2 FTS or 8:2 FTS had such low concentrations in soil that they were not quantified, might be linked to the replacement of masses in the central area and the depth of sampling. Other important factors are that AFFF containing PFOS had been used most of the time at this fire fighting training site, and that PFC compounds might be more retained in the peat soil with such high TOC level. In recent analyses at this training station by Sweco (appendix A) 6:2 FTS was measured to have a concentration of 0.4 µg/kg in soil from trial pit 17 (100-200 cm). The compound was also detected in groundwater of trial pit 13 a (the west side of the central training area) < 0.075 µg/l. Trial pit 17 was close to the site sampled for batch and column experiments, while trial pit 13 was a little further away from this site (***Figure 10***).

In all soil samples from Bergen and Kristiansund the eight compounds PFBA, PFPeA, PFHxS, PFHxA, PFHpA, PFOA, PFOS and PFNA were found. A large variety of compounds could be expected from samples of both airport fire fighting training stations, as the samples had a high total organic content (TOC > 8.55 %), and the stations have been used relatively recently. The two airport fire fighting training stations have had a simultaneous active period of nine years. Despite that 8 similar compounds are quantified at both fire fighting training stations, the concentration levels of the different PFCs does not have a common trend. The concentration levels of the eight common compounds rather followed opposite trends of concentration levels for the two sites.

Besides PFOS, some other compounds were common for all the soil samples from the three airports. PFHxS is quantified in all samples with the highest concentration in Ksund (> 5.8 times higher than other sites). The K_d values for this compound, calculated from soil and water samples of the seven sites, were in the range from 8.13 l/kg to 60.4 l/kg. These are relatively high K_d values compared to the compounds of similar carbon chain length. The presence of PFNA in all samples, except Ksand 30, can likely be linked to the chain length of

nine carbons, and a relatively high sorption as seen from the range of K_d for the all three soil types 21.3 -145 l/kg. The compound PFDA was quantified in all samples from Bergen and the oldest training site of Ksand (15 A and B), though these two sites do not have simultaneous active period as training ceased in 1985 at Ksand (15 A and B). PFDA has a carbon chain length of 10 atoms, and is the compound with highest calculated K_d both in soil from Kristiansand (KSA 15 A: 36.0 l/kg) and Bergen (BP3: 753 l/kg).

6.2 Batch Experiments

6.2.1 Relative distribution of PFCs in soil and water

When comparing the relative distributions of PFCs in soil and water samples from the batch experiments (***Figure 31***, ***Figure 32*** and ***Figure 33***), it is clear that the PFCs with a carbon chain shorter than eight carbons have a higher relative contribution to the ΣPFCs in the water phase than in soil. This observation includes 6:2 FTS with a total of eight carbons, whereas only six of them are fluorinated. For PFOA (C8) there is no clear relationship between the relative soil and water concentrations. The longer carbon chain compounds PFOS (C8), PFNA (C9), 8:2 FTS (C10) and PFDA (C 10) have a higher relative contribution to the ΣPFCs in soil samples than in the water samples. This indicated a stronger sorption of the long carbon chain PFCs, and is in agreement with observations reported previously (Niva, 2007; Klif, 2008c; Ahrens et al., 2010; Gellrich et al., 2012b).

6.2.2 Amount of individual PFCs leached out from soil

The total amount of individual PFCs leached out of soil from all samples, except KSA30 with the lowest TOC level, were decreasing with increasing carbon chain length of the compounds. It is clear that most of the total PFCs that were present in soil sample KSA30 have been washed out, independent of the carbon chain length. For samples KSA15 A and B, the

compound with shortest carbon chain length (PFHxS (C6)) of those present in soil, was most highly leached. The samples from Bergen show high retention of PFHxS (C6) and the compounds of carbon chain length longer than C8. However, in samples BP7 and BP3, the compound 6:2 FTS (C8) had leached out relatively much of the amount in soil compared to compounds of equal carbon chain length. In these samples, the compound PFPeA (C5) had leached out more than PFBA (C4) with shorter carbon chain length. In the sample from Kristiansund the compounds show similar trends as samples from Bergen, except for the higher degree of leaching for PFHxS (C6), PFOA (8) and PFNA (C9). The compound PFPeA (C5) had leached out more than both PFBA (C4) and PFBS (C4) in the Kristiansund sample.

6.2.3 Relationship between PFC sorption and carbon chain length

In general the compounds with a carbon chain length shorter than C6 (when not including PFHxS) have almost completely leached out of the soil. The organic carbon content of the soil had little influence on the leaching of these compounds. Compounds of increasing carbon chain length are increasingly stronger retained in the soil, and thus have higher potential for long persistence in soil, which can result in slow long-term leaching. This is supported in a study by Higgins et al. (2006) where they found that the sorption of PFCs increased considerable with increasing carbon chain length of the compounds. However, in Kristiansand samples with low organic carbon content, the compounds of longer carbon chain length had a higher total leaching out of soil. In the Bergen and Kristiansund samples, the sulfonic compounds PFHxS and PFOS had higher potential for long term leaching from soil compared to the acidic compounds of similar carbon chain length. For all samples the amount of PFOS that has leached out of soil is clearly decreasing with increasing organic carbon content of the soil, and the compound are among the most retained compounds in samples BP3, BP13 and KSUND.

It was in general found that the K_d values calculated for the acidic compounds in each sample were increasing with increasing carbon chain length, except for sample KSA30. The K_d values for the sulfonic compounds PFOS and PFHxS were higher than for the acidic compounds of

similar carbon chain length. The compound PFBA (C4) had higher K_d value than PFPeA (C5) in most samples. The opposite was expected as both compounds are carboxylic acids, and PFBA (C4) has three fluorinated carbons in the chain, while PFPeA (C5) has four fluorinated carbons. In the literature Higgins et al. (2006) also found that sulfonic acids have a higher sorption than carboxylic acids of equal carbon chain length.

The difference of log K_{oc} with each CF_2 added in the carbon chain was calculated. Results are shown in appendix C. Since the sulfonic compounds were found to have a higher sorption, calculations were only for the perfluoroalkyl acids. An increase of log K_{oc} with increasing perfluoroalkyl chain length was found for all compounds except PFBA. PFBA had high K_d values relative to its carbon chain length as discussed, and excluding PFBA, the range for increase of K_{oc} with each added CF_2 to the carbon chain were 0.1-0.7 log units. Higgins et al. (2006) found an increase of log K_{oc} with increasing perfluoroalkyl chain length for the acidic compounds. For each added CF_2 in the carbon chain, there was an increase of K_{oc} with 0.5-0.6 log units.

6.2.4 Equilibrium partitioning coefficients (K_d) in relation to TOC level

For the compounds PFOS, PFNA and PFDA, there was a positive linear correlation between log K_d and TOC. Increasing organic carbon content in the soil increases the sorption these compounds, and thus the concentration in water was dependent on the TOC level in the soil. For PFOS it was evident from the relative contribution to the ΣPFCs both in water and soil samples that the contribution of the compound markedly decreases with increasing TOC level. Such apparent relationship was not observed for the relative distribution of any other compounds to the ΣPFCs in soil or water.

It was previously discussed why PFNA and PFDA were found in the samples KSA15A and B from the fire fighting training station used before 1985, and not in the sample KSA30 from the training site used from 1985-2008. The linear relation of K_d and TOC for these compounds, PFNA and PFDA, supports that the slightly lower TOC in sample KSA30 could explain this finding. These compounds are highly dependent on the TOC level in the soil.

6.2.5 Relationship between total concentrations of each PFC and concentrations of the PFCs in water

The positive linear relation between the concentrations in soil and in water for the three acidic compounds, PFPeA, PFHxA, PFHpA, means that the total concentrations in soil can be determining the capacity for leaching, not other soil characteristics like TOC. This can explain why PFPeA has lower K_d values in the different soil samples than PFBA, as the soil concentrations of PFPeA are higher in all soil samples than the concentration of PFBA. The K_{oc} values for PFPeA, PFHxA, PFHpA increased with 0.1 log units for each added CF_2 in the carbon chain, so there was also a dependency on the chain length. This was, however, a smaller increase in log K_{oc} than for the other acidic compounds of longer carbon chain length PFOA, PFNA and PFDA.

6.2.6 Relationship between concentration of calcium and PFC concentrations in water

Increased positive charge of the mineral surfaces with high calcium content, can be explaining the increased sorption observed for the compounds PFDA, PFNA, 8:2 FTS and PFOS at high calcium concentrations in soil. From these observations it is clear that other soil characteristics than TOC level are influencing the sorption of PFCs. Higgins et al. (2006) found increased sorption of long carbon chain PFC compounds (≥ 8C) with increased calcium concentration in the solution, and this was also observed for PFOS in an experiment by (Tang et al., 2010). The observations of increasing concentration in water for the compounds PFHxA and PFBA at higher calcium concentrations in soil can possibly be caused by preferentially binding of the compounds with longer carbon chain length, or stronger anionic charge, to the mineral surfaces. Thus they are taking up the available space before these two shorter carbon chain compounds. The experiments of Higgins et al. (2006) and Tang et al. (2010) included only PFCs with carbon chain length higher than C8, and it is possible that PFCs of short carbon chain lengths have a different behavior, or that the observed behavior of these short chain compounds (< 7C) are related to chemical interaction with the longer chain compounds.

The calcium concentration in soil and in water samples showed a positive linear correlation, except for samples KSA 15 A and B. If all samples showed a positive linear correlation for the calcium concentration in soil and in water, it would be expected that the behavior of PFCs with increasing calcium concentration in water was similar to the behavior observed for increasing calcium concentrations in soil. The expected behavior was only observed for PFOS, 8:2 FTS and PFBA (***Figure 44***). It seems that the concentration of PFDA, PFNA, and PFHxA in water when calcium concentration in soil or water increases are greatly influenced by the samples KSA15 A and B.

6.3 Column experiments

6.3.1 Total PFC concentrations and relative concentration distribution in leachate over time

Although there was a general decrease in the ΣPFC concentrations in leachate of the soil columns over time, the leaching of the individual compounds varied considerably. Concentrations of some of the PFCs decreased over time, while others were stable or even increased. The difference in the velocity of total PFCs leaching out of the columns from the three sites over time, are likely related to the total organic carbon content of the soil, and the total amount of water flown through the columns. Before the infiltration of water into the soil columns, the soil contained varying amounts of water in the porespaces due to the water content of the soil. This water had been in the soil pores from the day of sampling, and for an unknown time before sampling. The porewater present at the start of the column experiments could have affected the initial concentrations of the compounds in leachate of all columns.

The columns from Kristiansand (***Figure 52***) had the highest ΣPFCs leaching out during the experiment, and the highest and fastest decrease in the ΣPFCs leaching out during the experiment. This soil had the lowest total organic carbon content, and the highest total amount of water through the columns. It is clear that with the low retention in the soil, and high flow-

velocity of these columns, the bulk of the ΣPFCs (average between columns 76 %) leached out within a flushing of 9 porevolumes. PFOS was totally dominating in all samples of leachate from the Kristiansand columns, and the low retention of the compound in soil can be resulting from the low TOC level, combined with high PFOS concentration in soil of the columns, and the low variety of other PFCs in soil. The low variety of compounds in most samples of leachate of columns from Kristiansand might be related to the high water flow-velocity, and the low soil concentrations of other PFCs than PFOS. The average retention time for water in these columns were 18 hours, which likely was too short for the PFCs to reach the partitioning equilibrium between soil and water. As previously discussed, for batch experiments, 10 days were used to ensure that the PFCs reached the partitioning equilibrium (Higgins et al., 2006). However, two samples of leachate from these columns had a higher variety of PFC compounds. It was thought that these water samples with higher varieties resulted from variations in water flow-velocities (deviations from the average flow-velocity) through columns during the experiment, however, such relationship were not found. There was not found any relationship between water samples with higher PFC varieties and levels of dissolved organic carbon either. The DOC levels of L/S 2 were only slightly higher than in leachate of batch experiments with soil sample KSA30 at L/S 10, and the DOC levels decreased steady with time (see ***Table 13*** or appendix C). Before the infiltration of water into the soil columns from Kristiansand, the soil contained around 50 % water in the porespaces due to the water content of the soil. The compounds present in soil were likely in equilibrium with this water before the experiment started, and a higher concentration could have been expected in the first sample of leachate from the columns. This was only seen in leachate of column KSA30-A. High concentrations of PFOS leaching out from the soil increases the difficulty of quantifying other PFCs present at much lower concentrations. Leachate from column KSA30-A had higher variety of PFCs in the first sample, and lower PFOS concentration than for the first sample of KSA30-B. The low variety of compounds in the first sample of leachate from KSA30-B might be resulting from the high concentrations of PFOS. The LOQ were highest for PFC compounds in the first leachate sample from KSA30-B (appendix C), and some compounds might be present in concentrations close to LOQ. For both columns the water samples taken after 46 porevolumes had lower PFOS concentrations, and LOQ for the compounds were lower, it is therefore expected that other PFCs present was

easier to quantify. The LOQ were lowest for the leachate of KSA-B after 46 porevolumes, and this sample had the highest variety.

Columns from Bergen (***Figure 53***) had the second highest ΣPFC concentrations in leachate during the experiment, and the second highest decrease in ΣPFCs leaching out during the experiment. This soil had a relatively high total organic carbon content, and the second highest total amount of water flown through the columns. Before the infiltration of water into the soil columns, the soil contained around 50 % water in the porespaces due to the water content of the soil. The leachate within 0.9 porevolumes was likely consisting partly of this water that was already in equilibrium with the PFCs in soil. The retention time of water in these columns were approximately 7 days for BP3-A and 8 days for BP3-B. This is close to the number of days needed to ensure that the PFCs reached partitioning equilibrium between soil and water. The shorter carbon chain compounds (< C8) were not retained in this soil, and the bulk of these compounds leached out in 0.9 porevolumes. The bulk of 6:2 FTS had leached out in 1.8 porevolumes, and the retention of the compound were low. When water was flushed through the columns, the dynamic system constantly adjusted toward a new partitioning equilibrium. The soil concentration of many short carbon chain compounds and 6:2 FTS decreased with time, and the equilibrium between the compounds left in soil and water constantly changed according to the new conditions. PFOS and longer carbon chain compounds adjusted to the changing equilibrium conditions by leaching to a higher degree over time. The dominance of PFOS after 4.5 porevolumes might be controlled by the high concentration of PFOS in the soil from Bergen site BP3.

Columns from Kristiansund (***Figure 54***) had the lowest ΣPFC concentrations in leachate during the experiment, and the lowest decrease in the ΣPFCs leaching out over time. The total organic carbon content was the highest, and the average water flow-velocity through these parallel columns was the slowest. With an average retention time of water in the columns of approximately 32 days for KSU-A, and nearly 27 days for KSU-B, the time for partitioning equilibrium were reached. Before the infiltration of water into the soil from these columns, the soil of KSU-A contained 63 % and KSU-B contained 91 % water in the porespaces due to the water content of the soil. As only 1.2 porevolumes of water went through the columns, much of the leachate throughout the experiment was from water already contained in the columns

before sampling. Similar to columns from Bergen, the carbon chain length was controlling the leaching of the compounds. Different from columns from Bergen was that PFNA had the highest relative contribution of long carbon chain compounds over time, instead of PFOS. The concentrations of PFNA in soil from Kristiansund were high compared to the other soil samples, and PFOS had the lowest concentration in this soil.

6.3.2 Comparing the results of batch experiments and column experiments

In the batch experiments it was attempted to achieve equilibrium between soil and water phase by a contact time of 10 days. Contrary to this, column leaching is a dynamic process with variable contact time, and it not certain that equilibrium will be reached. A comparison of the result from the batch and column results showed strong differences between the various soils. Some of the PFCs included in this study were not detected in soil, but detected in leachate samples from the batch or column experiments. This is a result of different levels of quantification (LOQ) in the different analysis methods. In addition has the presence of one compound (e.g. PFOS) in a very high concentration resulted in increased LOQ for other PFC compounds.

Kristiansand (KSA30)

The four compounds found in soil, PFOS, PFHxS, 6:2 FTS and 8:2 FTS, were the main compounds found in leachate of both batch and column experiments. The average ΣPFC concentrations in leachate of the columns after 9 porevolumes (L/S ratio 2) was around four times higher than in leachate of the batch experiment (L/S ratio 10). After 18 porevolumes (L/S ratio 4) the ΣPFC concentrations was lower than in batch experiments. The decrease to a lower total concentration than in the batch experiment so early in the column experiment indicates that the PFC compounds were little retained in this soil from this site. The water flow-velocity through soil columns was thus controlling the total leaching. When comparing batch and column experiments, the relative distribution of PFCs in leachate from soil sampled

at KSA30 is similar for all samples. As discussed, in the batch experiment the compounds had time to reach partitioning equilibrium between soil and water, still PFOS was dominating both from leachate of the stationary batch experiment, and over time from the column experiment. The compound had the dominating contribution in the soil from site KSA30, and was easily released from this sandy soil type.

The average amount of PFCs (%) leached out of the initial amount in soil from site KSA30 using batch and column experiments is compared in ***Figure 64***. From batch experiments the four compounds leached out in very equal relative amounts (66-75 %) of the content in soil. For the parallel columns, the four compounds leached out in very different amounts from soil. The compounds 6:2 FTS and PFOS leached out more from columns than in the batch experiment, while PFHxS and 8:2 FTS leached out much lower percentage from columns than in batch experiment. The low percentage leaching for PFHxS and 8:2 FTS from columns can be resulting from the low retention time for water. These compounds were only quantified in 2-3 water samples of each column, and it is also possible that the concentration levels of these two compounds in leachate of most samples were right under LOQ. Using the LOQ value to calculate the total percentage leaching from soil, PFHxS would reach around 53 %, however, 8:2 FTS would only reach around 25 %.

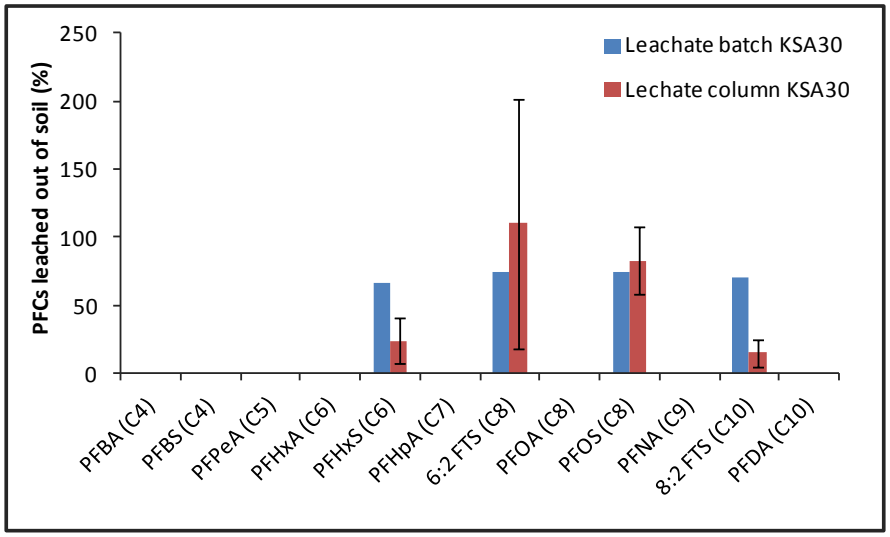


Figure 64: The total amount of PFCs (%) leached out of the initial amount in soil from site KSA30 using batch (average of n=3) and column (average of n=2) experiments. PFCs are organized according to increasing carbon chain length of the individual compounds.

Bergen (BP3)

11 compounds were found in soil from site BP3, while the compound PFBS was < LOQ. 12 compounds, including PFBS, were found in leachate of both batch and column experiments. The sum of PFC concentrations in leachate of the parallel columns after 0.9 porevolumes (L/S ratio 2) was two times higher than in leachate of the batch experiment. After 2.7 porevolumes (L/S ratio 6) the total concentrations were close to those for batch (L/S 10). The relative distribution in leachate of batch was most similar to the distribution in samples after 0.9 and 1.8 porevolumes (L/S ratio 2 and 4) of leachate from columns. 6:2 FTS dominated these samples of leachate. From 2.7 to 4.5 porevolumes the concentration of shorter carbon chain compounds are much lower than in batch experiments, and in addition PFOS dominates.

The amount of PFCs (%) leached out of the initial amount in soil from site BP3, using batch and column experiments is compared in ***Figure 65***. From batch experiments the compounds PFPeA, PFHxA and PFBA had leached out the most of the total content in soil, and PFDA and 8:2 FTS the least. From column experiments, the compounds with carbon chain length shorter than seven show very similar total accumulated amount in leachate as batch experiments. However, for the compounds PFOA and PFNA the total accumulated leaching were much higher from soil in the columns. The compounds PFHpA, PFOS, 8:2 FTS and PFDA also had higher total accumulated leaching from columns. In leachate of the columns the concentrations of these compounds were steady or increased over time, and the relative contribution in leachate increased over time, except for PFHpA. It can be seen from ***Table 13*** that the DOC level in leachate of columns from Bergen was increasing over time, and that the DOC level in the water sample at L/S ratio 10 from columns were higher than in leachate of batch with soil sample BP3. If the long chain compounds were bound to colloids in the leachate of columns, the increasing level of DOC over time would also likely have contributed to the increased leaching of long chain compounds over time. 3M (2003) reported that PFOS were bound to the surfaces of particles in solution. The calcium concentration was decreasing in leachate, and thus in soil of the columns over time (***Table 13***). It was found from batch experiments with all seven soil samples that the concentrations of PFOS, 8:2 FTS, PFNA and PFDA in water decreased with increasing calcium concentrations in soil. The long carbon chain compounds could also have been less retained over time as the calcium content was

washed out of the soil. 6:2 FTS had lower total accumulated leaching from columns compared to batch experiments.

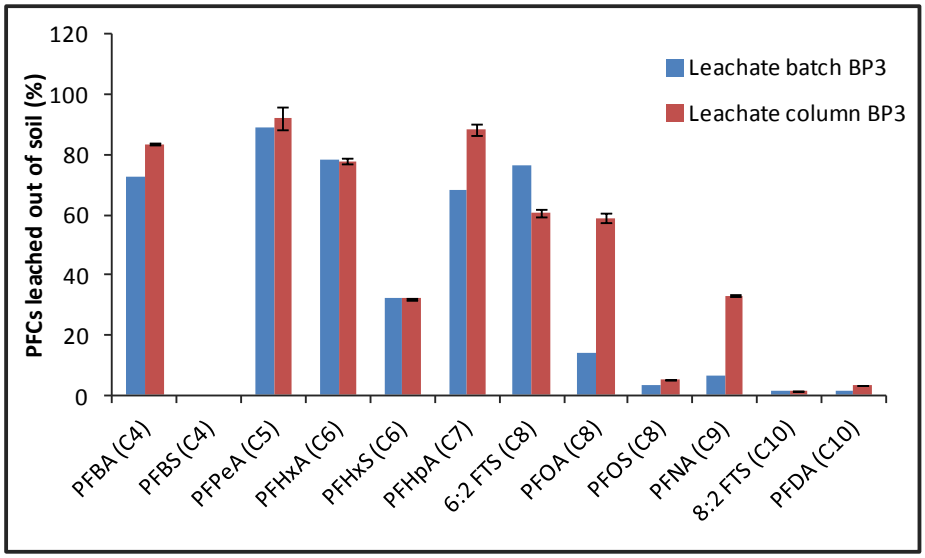


Figure 65: The total amount of PFCs (%) leached out of the initial amount in soil from site BP3 using batch (average of n=3) and column (average of n=2) experiments. PFCs are organized according to increasing carbon chain length of the individual compounds.

Kristiansund (KSU)

Nine compounds were found in soil from site KSU, and in leachate from the parallel columns. 10 compounds were found in leachate of batch experiments with soil form this site. The total PFC concentrations in leachate were relatively similar for the batch sample and the samples over time from columns. When comparing the relative distribution of PFCs in leachate of the batch and column experiments, the sample of leachate after 0.4 porevolumes (L/S ratio 2) are most similar to leachate of batch (L/S ratio 10).

The amount of PFCs (%) leached out of the initial amount in soil from site KSU, using batch and column experiments is compared in ***Figure 66***. The total amount of the individual compounds leached out of soil was in general higher for batch than for column experiments. The liquid to solid ratio of 10 were not reached for column experiments, and thus a lower total amount of individual PFCs leaching out of soil was expected for leachate of the columns. The

individual compounds leached out of soil from column experiments had very equal total amounts, in the range from 48 to 67 %, except PFOS which had leached out very little. However, the compounds PFOS and PFNA had leached out more from soil in the columns over time. PFOS and PFNA had increased concentrations and relative contribution in leachate of columns from Kristiansund over time. This was similar to what was observed for long carbon chained compounds in columns from Bergen, although stronger concentration increase in leachate of columns from Kristiansund. In leachate of columns from Kristiansund the DOC levels were decreasing over time, and much lower than in batch experiments with soil sample KSU (***Table 13***). The DOC level could therefore not explain the higher accumulated leaching of PFOS and PFNA in leachate of columns. The calcium concentration were decreasing over time (***Table 13***), and much lower than in leachate of batch experiments. PFOS and PFNA time could have been less retained in soil over time as the calcium content was washed out of the soil.

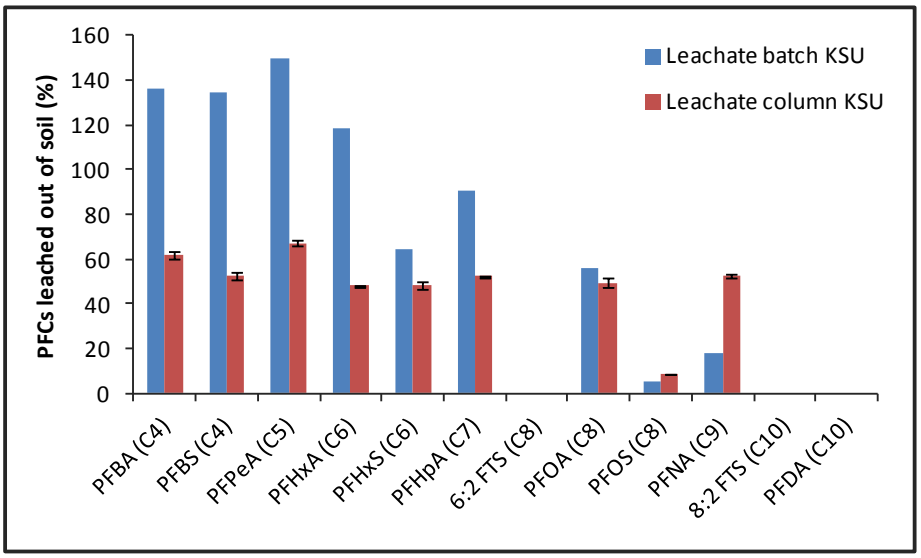


Figure 66: The total amount of PFCs (%) leached out of the initial amount in soil from site KSU using batch (average of n=2) and column (average of n=2) experiments. PFCs are organized according to increasing carbon chain length of the individual compounds.

Table 13: Calcium concentration (mg/l) and DOC concentration (mg/l) in water samples of batch (L/S 10) and column experiments (L/S 2 and 10) with soil from sites KSA30, BP3 and KSU.

Sample	Ca (mg/l)	DOC (mg/l)
KSA30 batch L/S 10	0.74	7.43
KSA30 column L/S 2	3.65	10.0
KSA30 column L/S 10	0.50	2.70
BP3 batch L/S 10	2.77	23.3
BP3 column L/S 2	12.5	21.5
BP3 column L/S 10	4.10	38.0
KSU batch L/S 10	6.20	210
KSU column L/S 2	1.70	61.5
KSU column L/S 6	0.97	45.0

6.3.3 Potential for long term leaching

Now that PFOS have been prohibited in fire fighting foam, it is interesting to evaluate the long term leaching of the contaminants stored in soil at the fire fighting training sites. Long term leaching from soil is depended on the chemical structure of the PFC, the soil characteristics as well as the hydrogeology in the polluted area.

The potential for long term leaching of the short carbon chain compounds (< C8) are very low. However, it is dependent on the groundwater flow-velocity and the PFC concentrations in soil. In the column experiments, the compounds with short carbon chain were very mobile in soil, and they leached out of the soil fast. They were thus not subjected to considerable sorption to organic carbon or mineral surfaces in the soil, and were not retained. In the soils types with higher TOC level, the longer carbon chain compounds (≥ C8) were increasingly retained, and therefore have a higher potential for long term leaching.

In leachate of columns from Bergen and Kristiansund, many of the short carbon chain compounds were found. The total accumulated amount of individual PFC was in general higher for columns from Bergen, as columns from Kristiansund only reached L/S 6. However, the leaching behavior of PFCs from these columns sampled at two different airports had many similarities. The velocity of the leaching of PFC compounds from the soil in columns from

Bergen and Kristiansand (***Figure 60***, ***Figure 61***, ***Figure 62*** and ***Figure 63***) followed a general order among the compounds:

- The compounds PFPeA, PFBA, PFBS, PFHxA and PFHpA, all with carbon chain length < 8C, leached out from soil the fastest.
- The compounds 6:2 FTS, PFOA, PFHxS and PFNA, with carbon chain length from C6 to C9, leached out from soil with intermediate velocity.
- The compounds PFOS, PFDA and 8:2 FTS, with carbon chain length from C8 to C10, leached out from soil the slowest.

The importance of carbon chain length for leaching behavior of PFCs was pronounced. Higher retention of PFHxS and PFOS than compounds of equal carbon chain length was also marked. In a study of sorption and desorption of PFCs Gellrich et al. (2012b) also found that the carbon chain length were important for the leaching of PFCs out of soil columns. They found that the short carbon chain compounds PFBA, PFBS, PFPeA, and PFHxA were not retained in soil, while PFOS and compounds of longer carbon chain length had slow desorption.

PFPeA were the compound with highest percent leached out of soil in L/S 2, and the compound with the highest total accumulated leaching from soil in columns from Bergen and Kristiansund. The leaching of PFPeA was, in the batch experiments, found to be dependent of the total concentrations in soil. The compound had higher concentrations than PFBA in the soil samples BP3 and KSU, and the soil concentrations could be the explanation for the leaching behavior of PFPeA from columns. The compounds with intermediate leaching velocity from the soil in columns from Bergen and Kristiansund, like for instance the compound PFHxS (C6) (***Figure 67***), leached out a relatively low amount of the total amount in soil from all soil types. It is surprising that the highest total amount leached out of soil is from the soil with highest TOC in columns from Kristiansund. PFHxS leaches out more and faster from the Kristiansund columns, than from the columns of Kristiansand and Bergen. This can be related to the high concentration of the compound in the soil from Kristiansund, however, the compound have a higher potential for slow long term leaching from soil from Bergen.

PFOS, 8:2 FTS and PFDA are the compounds that leached out slowest from the soil types with high TOC level. Of these three compounds, PFOS has the highest concentrations in soil,

and is thus the compound expected to leach out of soil the longest. 8:2 FTS has potential for long term leaching from the soil from Bergen airport, where soil concentration of the compound was high.

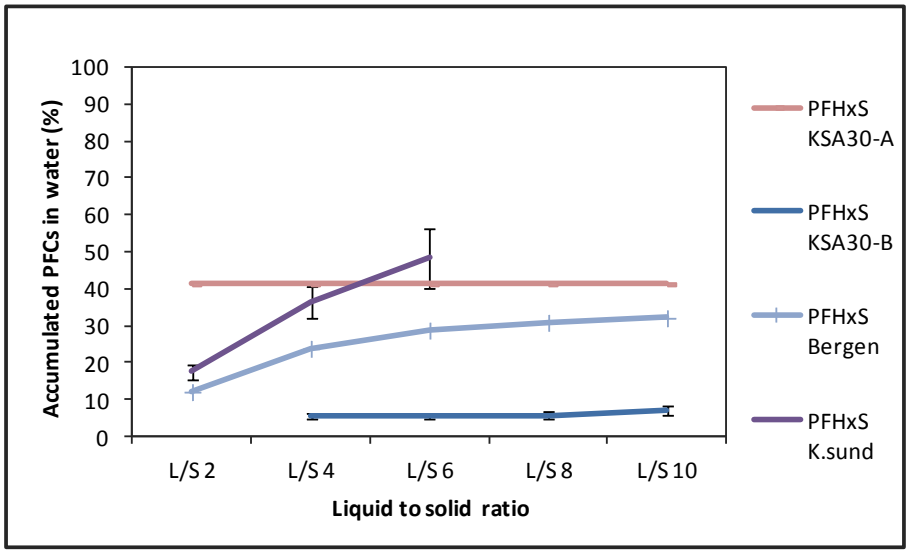


Figure 67: The total amount of PFHxS (%) leached out of the initial amount in soil from the three airports.

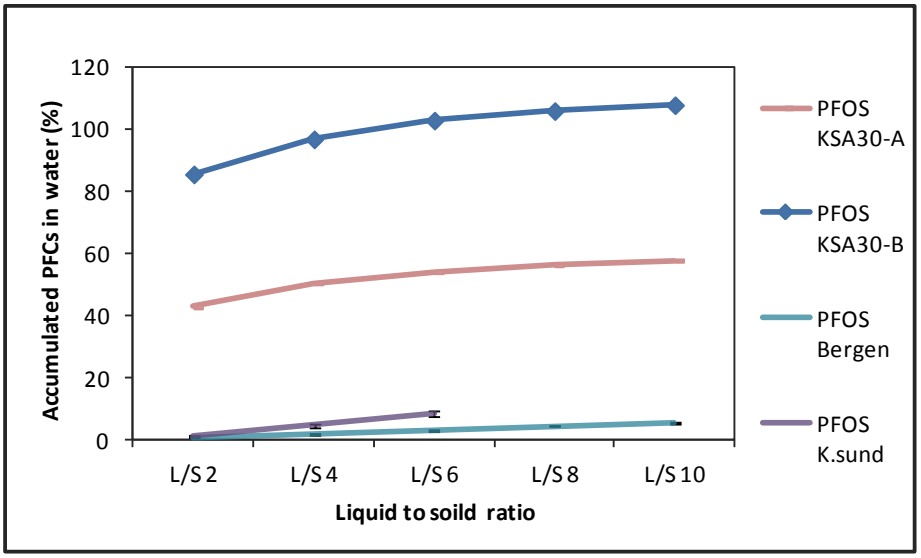


Figure 68: The total amount of PFOS (%) leached out of the initial amount in soil from the three airports.

The total amount of PFOS leached out of the initial amount in soil from the three airports is compared in ***Figure 68***. The figure shows that leaching of PFOS from the columns depended on the TOC level of the soil, and the total concentration in soil. It is difficult to interpret and evaluate the leaching behavior of PFOS in leachate of columns from Kristiansand due to the large variations between the columns. However, the average total leaching of PFOS was > 80 % of the initial amount in soil, and with the velocity of water through the columns PFOS was leaching out fast. The retention time for water in columns of 18 hours are much shorter than for groundwater conditions in the environment Moody et al. (2003). Given the high concentrations in the soil and low TOC levels, the potential for long term leaching of PFOS is determined by the groundwater velocity at the site. From the organic rich forest soil in columns from Bergen only around 6 % of the total PFOS leached out during the experiment. The relatively low percentage leaching of PFOS from these columns were the concentrations in soil was high, shows that this is a potential source of long term leaching. Peat soil in columns from Kristiansund had higher percentage leaching of PFOS than the columns from Bergen. As the columns from Kristiansund had lower water flow-velocity, this was caused by the low concentrations of PFOS in these columns. PFOS in soil from Kristiansund is not likely to be a source of long term leaching, it is however dependent on the drainage at the site.

6.4 Sources of error

The most important source of error for samples in batch experiments are the use of polysulfone filter for water samples KSA30. It was showed in the methods section, that this type of filter likely retains PFOS to a higher degree than GF/C filter. This could have lead to lower concentrations of PFOS in water sample KSA30, and thus higher calculated K_d value for PFOS in this sample. Another source of error for samples in batch experiments are the use of more glass containers for water samples BP13 and KSUND. This could have lead to lower water concentrations of PFOS, and possibly other PFCs, and higher K_d values for compounds in these samples.

The PFC concentrations found in soil sample KSA30 from Kristiansand are a possible source of error for both batch and column experiments. The columns from Kristiansand had large differences between the accumulated leaching of individual PFCs from the soil, especially for PFOS and 6:2 FTS. When comparing with the total amount leached out from soil sample KSA30 in the batch experiments (***Figure 64***), the differences were obvious. During field work the columns were sampled within a distance of 50 cm from each other, and soil for batch experiment was collected in the same one m^3 of soil. There could have been large differences in concentrations levels of PFCs in soil samples from close distances at this particular site. If there are such large concentration variations at the site, the analysis of soil samples from this site might not be representative for the actual soil used in the laboratory experiments. From the analysis of PFOS in soil from site KSA30, the concentration of PFOS had a coefficient of variation around 30 %, and 6:2 FTS was only quantified in one of the three analyzed soil samples. The differences between the parallel columns could also have been caused by high uncertainty in the analysis of leachate samples. The high concentrations of PFOS in the leachate can, as discussed, increase the difficulty of quantifying compounds present in low concentrations. Although there were large differences between the parallel columns, the high total accumulated leaching and very little increase of accumulated leaching over time for PFOS and 6:2 FTS, shows that the velocity of the leaching was fast for these compounds. From the analysis result (appendix C) it is clear that PFHxS and 8:2 FTS had concentrations in leachate that were close to LOQ, and the accumulation over time was likely higher.

7. Conclusions

Per- and polyfluorinated compounds are a broad and heterogeneous group of compounds, that can be divided into many subgroups based on functional groups. It is the different physicochemical properties of the individual compounds, and the effects of their chemical interaction that determine their fate when released in the environment. Leaching of PFCs from polluted soil is dependent on the soil characteristics, the sorption behavior of the individual compounds, and the compounds interaction, as well as hydrological conditions. The soil characteristics are important since the hydrophobic alkyl tail of these compounds can sorb both to organic carbon in the soil and mineral surfaces. Being anionic compounds, with a strongly hydrophilic organic functional group, sorption of PFC compounds can also be influenced by many other factors; for instance the pH and ion composition of the solution.

It was in this Master thesis, through batch and column experiments, observed that the carbon chain length seemed to be the most important structural feature affecting the leaching of PFCs. At equilibrium partitioning of the PFCs between soil and aqueous phase, compounds with shorter carbon chain length (C4-C7), including 6:2 FTS (C8), had a larger relative contribution to the ΣPFCs in the aqueous phase than in soil. The compounds with longer carbon chain length (C8-C10) had lower relative contribution to the ΣPFCs in water than in soil, and thus seemed to be stronger retained in the soil. Column experiments confirmed the importance of carbon chain length for the leaching behavior of PFCs. There was a general decrease in the relative contribution of shorter carbon chain compounds (< C8), including 6:2 FTS (C8), to the ΣPFCs in leachate from the columns over time, while the relative distribution of the long carbon chain compounds (≥ C8) to the ΣPFCs in leachate from soil increased over time.

The partitioning equilibrium coefficients (K_d) of the acidic PFCs between porewater and the various types of soil showed a strong relationship with carbon chain length of the compound. The log K_{oc} value increased with 0.1-0.7 log units for each added CF_2 in the carbon chain of the acidic compounds, except for PFBA, which had a higher sorption than compounds of equal carbon chain length. The total amount of individual PFCs leached out of the initial amount in soil at equilibrium was decreasing with increasing carbon chain length of the

compounds. However, more of the longer carbon chain compounds had leached out from the soil in the columns. This could have been a result of the decreasing calcium concentrations in soil over time, as the long carbon chain compounds seemed to be strongly affected by the calcium concentration in soil and aqueous phase. Water concentration of the long carbon chain compounds (≥ C8) PFOS, 8:2 FTS, PFNA and PFDA decreased with increasing calcium concentration in soil of batch experiments, and increased with decreasing calcium concentration in soil of column experiments.

There were also found differences in the leaching and sorption behavior between compounds of similar carbon chain length, with different organic functional group. The sulfonic compounds PFOS and PFHxS were higher retained in soil than the acidic compounds of similar carbon chain length.

The acidic short carbon chain compounds (< C8) showed dependence on the total PFC concentration in soil for dissolving into the water phase, except PFBA. The compound PFPeA (C5) had a slightly lower retention in soil than PFBA (C4). This was likely because PFPeA depended on the total concentration in soil, and had a higher concentration in all soil samples than PFBA.

TOC level of the soil samples were also found to be important for leaching of PFCs. The compounds were least retained in the soil with lowest TOC level, and leached high levels out of the soil independent of the carbon chain length. The soil types with higher TOC levels in general had much higher retention of PFCs, and more of the short carbon chain compounds present. The long carbon chain compounds PFOS, PFNA and PFDA were the individual compounds most dependent on the TOC level in the soil for sorption. From the soil with very low TOC level, the leaching of PFCs depended on the water flow-velocity. Therefore, in areas where the groundwater flow-velocity is high and the soil has low TOC content, PFCs can spread far from the source independent of carbon chain length. In soil with higher TOC levels, the groundwater flow-velocity would be most important for the leaching velocity of compounds with low carbon chain length (< C8), and low retention in the soil. Compounds of longer carbon chain length have slower leaching out of soils with a high TOC content.

Considering the potential for long term leaching of PFCs, the compound structure, soil characteristics and the hydrogeological conditions are important. The most important soil characteristics seem to be the TOC level, the concentration level of calcium, as well as the concentration of the PFCs in the soil. The potential for long term leaching from soil is very low for the short carbon chain compounds (< C8) as the compounds were very mobile in soil independent of the TOC level, and they leached out of the soil fast. The compound PFHxS (C6), however, has a higher potential for long term leaching as it was stronger retained in soil than compounds of equal carbon chain length. In general, longer carbon chain compounds (≥ C8) have a higher potential for long term leaching. PFOS, 8:2 FTS and PFDA were the compounds that leached out slowest from soil with high TOC level. It was, however, PFOS that had the highest concentrations in soil, and were thus the compound expected to leach out of soil the longest.

The findings of this Master thesis can be used to evaluate the potential for spreading of PFCs with groundwater from soil. It was, however, observed that many factors controlled the leaching of PFCs, and such evaluation is not straight forward. As mentioned, the potential for spreading needs to be based on factors like the compound structure, soil characterstics, soil concentrations and composition of PFCs, hydrological regime, etc. It was clear that the results from the performed batch and laboratory experiments supplemented each other, and more research on the leaching of PFCs would increase the total understanding. More understanding is needed as a basis for evaluating the environmental risk of PFC polluted soil.

8. Recommendations for future work

The bulk of studies concerning the behavior, fate and transport of PFCs in soil has been on PFOS and PFOA. It was shown in this Master project that several PFCs are present in soil polluted by AFFF. Future work in this area should therefore include a larger range of compounds. Increasing restrictions for the use of PFOS and PFOA resulted in a shift towards production and use of fluorinated compounds of shorter carbon chain lengths. This eventually leads to the release of compounds in the environment that are more water soluble, and thus have a greater transport potential. The greater transport potential and increased usage of shorter carbon chain PFCs is equal to higher potential for human exposure to these compounds. Studies on microbiological degradation, sorption and groundwater transport of shorter carbon chain PFC compounds are therefore important for the evaluation of future potential environmental impact. Long carbon chain compounds are less mobile in soil, and thus have higher potential for persistence and long-term leaching. With regards to human health, the long carbon chain compounds are still of most concern as they are more persistent in the human body.

Compounds with higher sorption in soil exhibit lower potential for reaching groundwater and drinking water sources used by both animals and humans. The sorption of long carbon chain PFCs have been found to increase with increasing calcium content of the soil. The behavior of a group of PFC compounds with various carbon chain lengths in a soil and aqueous solution system can change with the ionic composition of the soil solution. For instance the effect of iron on sorption has been explored for PFOS and PFOA (Ferrey et al., 2012). This type of studies should include other PFCs to look at the behavior of the compounds when affected by chemical interaction, as some shorter carbon chain compounds seems to increase in the aqueous phase when calcium content in the soil increases. Concentration changes of other soil solution parameters, like magnesium or pH, that can affect the sorption behavior of anionic PFC compounds can also be studied. The common understanding is that low pH increases the sorption of anionic PFC compounds. However, for a soil or solution with many PFC compounds of various carbon chain lengths, the influence of solution pH on the sorption and leaching behavior of individual compounds is not clear.

The compounds 6:2 FTS and 8:2 FTS have replaced PFOS in aqueous film forming foam used at Avinor`s fire fighting training stations. It was clear from the laboratory batch experiments that 6:2 FTS had a higher relative contribution in water than soil, and that 8:2 FTS was strongly retained. In the column experiment, however, the leaching of 8:2 FTS increased over time. The use of these compounds have increased, still knowledge on the consequences of the release and spreading of these compounds in the environment is limited. More research, on for instance the biological impacts, is needed as there at the moment are no clear regulations concerning the production, use and disposal of these compounds. It has been observed that 8:2 FTOH can convert into PFOA through intermediate steps in the environment. Both 6:2 FTS and 8:2 FTS are fluorotelomers, and the structural features are very similar to FTOH compounds with two non-fluorinated carbons in the organic functional group. Knowledge on the conversion and degradation of 6:2 FTS and 8:2 FTS is important, and as 8:2 FTS is a sulfonic compound with 8 fluorinated carbons in the alkyl chain, the possibility of conversion of this compound into PFOS should be further studied.

Remedial measures for PFC polluted soils are yet in the test out phase, and studies that can increase the knowledge on how to handle highly contaminated sites are needed. Fate and transport models for PFC polluted soils should be developed, so that changing parameters in the soil can be studied with respect to environmental spreading of PFCs and development of remedial measures.

It is clear that it is important to increase the knowledge on the environmental behavior of the PFCs types that are being released today, and those that already have been released, and are widespread in the environment. Screening of the environmental levels and levels in humans, as well as toxicity studies for a broader range of PFCs is needed as a basis for forming regulations of these compounds. The research that has been done regarding persistence, toxicology and bioaccumulation of PFOS and PFOA indicates that it is important to prevent further environmental spreading of PFCs. This can only be prevented by regulations applying to the production of the compounds of concern. In the mean time it is important to focus on making people aware of what products that are containing PFCs, and safe disposal of such products. Also remedial measures should be taken in areas with high concentrations of PFCs in soil, and in areas where the leaching and transport potential of the compounds are high.

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10. Appendices

10.1 Appendix A

10.1.1 The new fire fighting training station at Bergen Airport Flesland

Table 14 shows the concentrations of PFOS and PFOA found in the previous analysis of soil from the sites sampled for batch and column experiments (Avinor, 2011c). Sample depth is similar to samples for the master project. Groundwater concentrations are also shown in the table. The highest measured concentration of PFOS was 8250 µg/kg in top soil at site FLNF P3 (see ***Figure 7***). Avinor (2011c) report that during the last seven years the average amount of AFFF released at the new fire fighting training station was 2070 l/yr.

Table 14: Sample depths and concentrations of PFOS and PFOA in previous soil samples at the new FTS of Bergen airport, together with measured concentrations in groundwater (Avinor, 2011c).

Previous soil measurements at the new FTS			
Site name	**PFOS concentration**	**PFOA concentration**	**Depth (cm)**
FL-NF-P3-04	8250 µg/kg	n.d.	0-20
FL-NF-P7-08	1290 µg/kg	3.7 µg/kg	10-20
FL-NF-P13-14	1100 µg/kg	8.3 µg/kg	5-15
Brønnfelt 3 Groundwater	5.75 µg/l	0.18 µg/l	No data
Fles N K	4.51 µg/l	0.11 µg/l	No data

n.d = no data

Pictures from the sites sampled during field work, BP3, BP7 and BP13, are shown in ***Figure 69***, ***Figure 70***, ***Figure 71***, ***Figure 72*** and ***Figure 73***. The soil is described more closely in section 3. Description of the selected airports.

Figure 69: The soil collected at site BP3 (0-20 cm) was a thin layer on the bedrock that can be seen exposed in the pictures.

Figure 70: Site BP7 marked by the red arrow.

Figure 71: The soil collected at site P7 (0-20 cm) had more mineral grains in it.

Figure 72: Site BP13 was located on top of the mound with conifer trees as directed by the red arrow in the photo (left). Behind the mound used old fire extinguisher equipment could be found (right).

Figure 73: The samples of site P13 (0-10 cm) was sticky with a black color. Depth to bedrock was 10 cm at the maximum.

10.1.2 The old fire fighting training station at Kristiansund airport Kvernberget

Table 15: Sample depths and concentrations of PFOS, PFOA and 6:2 FTS in previous soil samples at the old FTS, together with measured concentrations in groundwater and surface water (Avinor, 2011b).

Previous soil measurements at the old FTS				
Site name	**PFOS**	**PFOA**	**6:2 FTS**	**Depth (cm)**
Shaft 12-2	1410 µg/kg	3.2 µg/kg	No data	100-200*
Shaft 12-3	1020 µg/kg	5.3 µg/kg	No data	250*
Shaft 17-2	160 µg/kg*	0.2 µg/kg	0.4 µg/kg	100-200
Well in shaft 9	31.7	0.255	< 0.075	No data
Well in shaft 13	40.5	0.225	< 0.075	No data
Well in shaft 18	6.47	0.034	< 0.015	No data
Vann 1 Surface water	1.91 µg/l	0.026 µg/l	No data	No data
Vann 2 Surface water	1.47 µg/l	0.03 µg/l	No data	No data
Vann 3 Surface water (Byskogbekken)	0.21 µg/l	0.007 µg/l	No data	No data

* Samples from shaft 17 were not analyzed at the time of sampling for this master project. Data from this shaft, from groundwater and for the compound 6:2 FTS is obtained from a new report from Krisiansund airport (Avinor, 2012e).

From the previous sampling in 2011 the type of material in the trial pit named shaft 12 was found to be mainly rocks and gravel down to 200 centimeters, and natural peat at greater depths. The analysis of soil from shaft 12 also showed concentration of PFOS > 1000 µg/kg, sample depths and concentrations of PFOS, PFOA and 6:2 FTS are shown in ***Table 15***. The trial pit named shaft 17 also had natural peat deeper than 200 cm, but the soil concentrations of PFOS or PFOA from this shaft were not analyzed at the time of sampling for this project. Based on this information it was likely that natural peat could be found at about 200 cm depth

in close vicinity of these two shafts. The new trial pit for the master thesis project was decided to have a location between shaft 12 and shaft 17.

Surface water samples had been taken close to the training station and in the river Byskogbekken. Measured PFOS and PFOA were indicating that spreading is going on. No groundwater samples had been taken at this training station at the time of sampling for this project.

Data for shaft 17 was obtained from a report published in January 2013 (Avinor, 2012e), including analyzes for the compound 6:2 FTS, and groundwater samples in shaft 9, 13 and 18 (see ***Figure 10***). Concentrations are included in ***Table 15***.

Figure 74: Excavator pressing a stainless steel cylinder into the natural peat (left). The student is happy with the successful soil sampling (and the weather) (right).

10.1.3 The fire fighting training station used until 1985 at Kristiansand airport Kjevik

From observations in field Avinor (2011d) assumes trial pit 15 to be the central area of the training station. The measured concentrations from this trial pit and from groundwater and river sediment are shown in ***Table 16***. The highest concentrations in trial pit 15 (1480 µg/kg) are close to 15 times higher than the value characterizing clean soil (< 100 µg/kg). Soil concentrations at different depths in this trial pit show relatively equal concentrations. Concentrations in groundwater downstream the site was found to be relatively high, while soil samples from the groundwater level do not show pollution by PFOS (BR42). PFOS was measured in one sediment sample from the river (E2), and spreading of the compound was evident.

Table 16: Sample depths and concentrations of PFOS and PFOA in previous soil samples from shaft 15, together with measured concentrations in groundwater and river sediment (Avinor, 2011d).

Previous PFC measurements at FTS used until 1985			
Site name	**PFOS concentration**	**PFOA concentration**	**Depth (cm)**
BØF-1:15-1	1150 µg/kg	<1.9 µg/kg	0-50
BØF-1:15-2	1220 µg/kg	<2.3 µg/kg	50-130
BØF-1:15-3	1480 µg/kg	<2.1 µg/kg	130-150
BR42 Groundwater	2.8 µg/l	0.052 µg/l	No data
E2 River sediment	17.4 µg/kg	< 2.1 µg/kg	0-10

10.1.4 The fire fighting training station used from 1985 to 2008 at Kristiansand airport Kjevik

The previously measured PFOS and PFOA concentrations from trial pit 30 and from groundwater and river sediment are shown in ***Table 17*** *(Avinor, 2011d).* Both PFOS and PFOA were measured in the groundwater in the well directly downstream the platform. Groundwater concentration of PFOS was high, and the concentration in the well 30 meters further towards the river was also high. It is clear that PFOS has been spread towards the river in the direction of groundwater flow. The compound was also detected in the river sediment of Topdalselva where the groundwater from the training station has its outlet. Supplementary pictures of the excavation work by the platform, and the filling of the stainless steel cylinders for column experiments are shown in ***Figure 75***.

Table 17: Sample depths and concentrations of PFOS and PFOA in previous soil samples from shaft 30, together with measured concentrations in groundwater and river sediment (Avinor, 2011d).

Previous measurements at FTS 1985-2008			
Site name	**PFOS concentration**	**PFOA concentration**	**Depth (cm)**
Shaft 30 BØF-2:30-2	1330 µg/kg	3.7 µg/kg	10-210
Shaft 30 BØF-2:30-3	141 µg/kg	< 1.9 µg/kg	210-230
B18 Groundwater	128 µg/l	1.24 µg/l	No data
B21 Groundwater	18.6 µg/l	0.305 µg/l	No data
E3 River sediment	21.7 µg/kg	< 2.3 µg/kg	0-10

Figure 75: Excavation work close to the training platform of FTS 1985-2008 (left). The excavator is pressing a stainless steel cylinder into the sandy soil (right).

10.2 Appendix B

10.2.1 Soil concentrations

The concentrations of 16 various elements and 12 PFCs in the soil samples are shown in ***Table 18*** (KSA30), ***Table 19*** (KSA15A), ***Table 20*** (KSA15B), ***Table 21*** (BP7), ***Table 22*** (BP3), ***Table 23*** (BP13) and ***Table 24*** (KSU).

Table 18: Element and PFC concentrations in soil in sample KSA30.

Jord KSA 30	Ksand 30 Jord	KSA-J2	KSA-J3	Enhet
Total tørrstoff	91.00	92.00	92.00	%
Arsen (As)	0.60	0.56	<0.55	mg/kg TS
Bly (Pb)	3.00	3.10	3.00	mg/kg TS
Kadmium (Cd)	0.34	0.37	0.38	mg/kg TS
Kobber (Cu)	1.30	1.80	1.70	mg/kg TS
Krom (Cr)	2.10	1.90	2.10	mg/kg TS
Nikkel (Ni)	1.20	1.30	1.30	mg/kg TS
Sink (Zn)	<11	<11	<11	mg/kg TS
Kvikksølv (Hg)	0.00	0.01	0.01	mg/kg TS
Aluminium (Al)	1 500	1600.00	1500.00	mg/kg TS
Jern (Fe)	3 100	3600.00	3000.00	mg/kg TS
Kalium (K)	340.00	370.00	290.00	mg/kg TS
Kalsium (Ca)	910.00	1000.00	1000.00	mg/kg TS
Magnesium (Mg)	730.00	840.00	710.00	mg/kg TS
Mangan (Mn)	44.00	48.00	41.00	mg/kg TS
Natrium (Na)	53.00	140.00	140.00	mg/kg TS
Silisium (Si)	140.00	120.00	140.00	mg/kg TS
Tørrstoff	-	91.50	92.30	%
6:2 Fluortelomersulfonat (FTS)	4.90	< 3	< 3.2	µg/kg tv
8:2 Fluortelomersulfonat (FTS)	10.20	7.80	< 4.3	µg/kg tv
Perfluorbutansulfonat (PFBS)	< 3.2	< 3	< 3.2	µg/kg tv
Perfluorbutansyre (PFBA)	< 2.2	< 2	< 2.1	µg/kg tv
Perfluordekansyre (PFDA)	< 2.2	< 2	< 2.1	µg/kg tv
Perfluorheksansulfonat (PFHxS)	4.50	5.60	< 3.2	µg/kg tv
Perfluorheksansyre (PFHxA)	< 2.2	< 2	< 2.1	µg/kg tv
Perfluorheptansyre (PFHpA)	< 2.2	< 2	< 2.1	µg/kg tv
Perfluornonansyre (PFNA)	< 2.2	< 2	< 2.1	µg/kg tv
Perfluoroktansyre (PFOA)	< 2.2	< 2	< 2.1	µg/kg tv
Perfluoroktylsulfonat (PFOS)	828.00	820.00	494.00	µg/kg tv
Perfluorpentansyre (PFPeA)	< 2.2	< 2	< 2.1	µg/kg tv
Sum PFC forbindelser eksl. LOQ	848.00	834.00	494.00	µg/kg tv
Sum PFC forbindelser inkl. LOQ	866.00	854.00	523.00	µg/kg tv

Blank spaces (-) means no data.

Table 19: Element and PFC concentrations in soil in sample KSA15 A.

Jord KSA 15 A	Ksand 15A Jord	KSA 15A-J2	KSA 15A-J3	Enhet
Total tørrstoff	86.00	87.00	86.00	%
Arsen (As)	0.89	0.87	0.87	mg/kg TS
Bly (Pb)	23.00	15.00	14.00	mg/kg TS
Kadmium (Cd)	0.09	0.07	0.07	mg/kg TS
Kobber (Cu)	1.40	4.40	3.50	mg/kg TS
Krom (Cr)	3.00	3.10	3.00	mg/kg TS
Nikkel (Ni)	2.10	1.90	1.70	mg/kg TS
Sink (Zn)	21.00	20.00	17.00	mg/kg TS
Kvikksølv (Hg)	0.02	0.02	0.03	mg/kg TS
Aluminium (Al)	3 500	3300.00	2700.00	mg/kg TS
Jern (Fe)	4 500	5800.00	4000.00	mg/kg TS
Kalium (K)	280.00	310.00	230.00	mg/kg TS
Kalsium (Ca)	1 200	1200.00	1100.00	mg/kg TS
Magnesium (Mg)	850.00	1200.00	700.00	mg/kg TS
Mangan (Mn)	54.00	71.00	44.00	mg/kg TS
Natrium (Na)	880.00	140.00	120.00	mg/kg TS
Silisium (Si)	190.00	180.00	170.00	mg/kg TS
Tørrstoff	-	86.00	85.50	%
6:2 Fluortelomersulfonat (FTS)	< 3.2	< 3	< 3.3	µg/kg tv
8:2 Fluortelomersulfonat (FTS)	< 4.3	< 3.9	< 4.4	µg/kg tv
Perfluorbutansulfonat (PFBS)	< 3.2	< 3	< 3.3	µg/kg tv
Perfluorbutansyre (PFBA)	< 2.1	< 2	< 2.2	µg/kg tv
Perfluordekansyre (PFDA)	5.40	3.90	4.50	µg/kg tv
Perfluorheksansulfonat (PFHxS)	11.50	9.90	9.40	µg/kg tv
Perfluorheksansyre (PFHxA)	< 2.1	< 2	< 2.2	µg/kg tv
Perfluorheptansyre (PFHpA)	< 2.1	< 2	< 2.2	µg/kg tv
Perfluornonansyre (PFNA)	5.10	3.40	3.80	µg/kg tv
Perfluoroktansyre (PFOA)	< 2.1	< 2	< 2.2	µg/kg tv
Perfluoroktylsulfonat (PFOS)	551.00	411.00	451.00	µg/kg tv
Perfluorpentansyre (PFPeA)	< 2.1	< 2	< 2.2	µg/kg tv
Sum PFC forbindelser eksl. LOQ	573.00	428.00	469.00	µg/kg tv
Sum PFC forbindelser inkl. LOQ	594.00	448.00	486.00	µg/kg tv

Blank spaces (-) means no data.

Table 20: Element and PFC concentrations in soil in sample KSA15 B.

Jord Ksand 15B	Ksand 15B Jord	KSA 15B-J2	KSA 15B-J3	Enhet
Total tørrstoff	87.00	88.00	87.00	%
Arsen (As)	0.85	0.78	0.91	mg/kg TS
Bly (Pb)	12.00	9.10	12.00	mg/kg TS
Kadmium (Cd)	0.05	0.05	0.06	mg/kg TS
Kobber (Cu)	<0.93	2.60	3.10	mg/kg TS
Krom (Cr)	3.10	2.50	3.10	mg/kg TS
Nikkel (Ni)	1.70	1.40	1.70	mg/kg TS
Sink (Zn)	15.00	13.00	16.00	mg/kg TS
Kvikksølv (Hg)	0.01	0.02	0.03	mg/kg TS
Aluminium (Al)	3 400	2400.00	2900.00	mg/kg TS
Jern (Fe)	4 300	3600.00	4400.00	mg/kg TS
Kalium (K)	240.00	210.00	260.00	mg/kg TS
Kalsium (Ca)	1 000	840.00	970.00	mg/kg TS
Magnesium (Mg)	770.00	620.00	720.00	mg/kg TS
Mangan (Mn)	47.00	37.00	48.00	mg/kg TS
Natrium (Na)	68.00	110.00	150.00	mg/kg TS
Silisium (Si)	160.00	180.00	150.00	mg/kg TS
Tørrstoff	-	88.10	87.40	%
6:2 Fluortelomersulfonat (FTS)	< 3.3	< 3	< 3.5	µg/kg tv
8:2 Fluortelomersulfonat (FTS)	< 4.3	< 4	< 4.6	µg/kg tv
Perfluorbutansulfonat (PFBS)	< 3.3	< 3	< 3.5	µg/kg tv
Perfluorbutansyre (PFBA)	< 2.2	< 2	< 2.3	µg/kg tv
Perfluordekansyre (PFDA)	3.50	2.40	2.60	µg/kg tv
Perfluorheksansulfonat (PFHxS)	7.80	6.70	6.00	µg/kg tv
Perfluorheksansyre (PFHxA)	< 2.2	< 2	< 2.3	µg/kg tv
Perfluorheptansyre (PFHpA)	< 2.2	< 2	< 2.3	µg/kg tv
Perfluornonansyre (PFNA)	4.30	2.60	2.70	µg/kg tv
Perfluoroktansyre (PFOA)	< 2.2	< 2	< 2.3	µg/kg tv
Perfluoroktylsulfonat (PFOS)	337.00	212.00	215.00	µg/kg tv
Perfluorpentansyre (PFPeA)	< 2.2	< 2	< 2.3	µg/kg tv
Sum PFC forbindelser eksl. LOQ	352.00	223.00	227.00	µg/kg tv
Sum PFC forbindelser inkl. LOQ	374.00	240.00	245.00	µg/kg tv

Blank spaces (-) means no data.

Table 21: Element and PFC concentrations in soil in sample BP7.

Jord BP7	BP7-Jord	BP7-J2	BP7-J3	Enhet
Total tørrstoff	65.00	65.00	61.00	%
Arsen (As)	2.10	1.40	1.60	mg/kg TS
Bly (Pb)	15.00	14.00	15.00	mg/kg TS
Kadmium (Cd)	0.11	0.09	0.11	mg/kg TS
Kobber (Cu)	10.00	10.00	11.00	mg/kg TS
Krom (Cr)	14.00	18.00	18.00	mg/kg TS
Nikkel (Ni)	16.00	13.00	15.00	mg/kg TS
Sink (Zn)	27.00	16.00	<17	mg/kg TS
Kvikksølv (Hg)	0.03	0.07	0.11	mg/kg TS
Aluminium (Al)	15 000	11000.00	10000.00	mg/kg TS
Jern (Fe)	13 000	10000.00	10000.00	mg/kg TS
Kalium (K)	1 400	670.00	600.00	mg/kg TS
Kalsium (Ca)	4 800	1800.00	2000.00	mg/kg TS
Magnesium (Mg)	6 000	3800.00	3500.00	mg/kg TS
Mangan (Mn)	150.00	81.00	80.00	mg/kg TS
Natrium (Na)	470.00	290.00	310.00	mg/kg TS
Silisium (Si)	280.00	290.00	300.00	mg/kg TS
Tørrstoff	-	65.30	63.60	%
6:2 Fluortelomersulfonat (FTS)	35.20	27.90	21.90	µg/kg tv
8:2 Fluortelomersulfonat (FTS)	6.30	18.80	< 4.6	µg/kg tv
Perfluorbutansulfonat (PFBS)	< 3.6	< 4	< 3.5	µg/kg tv
Perfluorbutansyre (PFBA)	10.10	13.20	10.90	µg/kg tv
Perfluordekansyre (PFDA)	9.70	7.70	8.20	µg/kg tv
Perfluorheksansulfonat (PFHxS)	14.40	15.30	12.70	µg/kg tv
Perfluorheksansyre (PFHxA)	10.40	12.20	10.20	µg/kg tv
Perfluorheptansyre (PFHpA)	5.00	6.80	4.20	µg/kg tv
Perfluornonansyre (PFNA)	9.70	8.80	8.10	µg/kg tv
Perfluoroktansyre (PFOA)	5.50	6.80	5.40	µg/kg tv
Perfluoroktylsulfonat (PFOS)	806.00	793.00	728.00	µg/kg tv
Perfluorpentansyre (PFPeA)	24.20	24.00	23.00	µg/kg tv
Sum PFC forbindelser eksl. LOQ	937.00	915.00	833.00	µg/kg tv

Sum PFC forbindelser inkl. LOQ	940.00	919.00	836.00	µg/kg tv

Blank spaces (-) means no data.

Table 22: Element and PFC concentrations in soil in sample BP3.

Jord BP3	BP3-Jord	BP3-J2	BP3-J3	Enhet
Total tørrstoff	50.00	47.00	47.00	%
Arsen (As)	3.60	3.60	4.20	mg/kg TS
Bly (Pb)	28.00	27.00	25.00	mg/kg TS
Kadmium (Cd)	0.12	0.14	0.14	mg/kg TS
Kobber (Cu)	2.70	<1.8	<1.8	mg/kg TS
Krom (Cr)	16.00	22.00	24.00	mg/kg TS
Nikkel (Ni)	11.00	13.00	19.00	mg/kg TS
Sink (Zn)	21.00	<22	<22	mg/kg TS
Kvikksølv (Hg)	0.09	0.10	0.10	mg/kg TS
Aluminium (Al)	18 000	19000.00	20000.00	mg/kg TS
Jern (Fe)	20 000	21000.00	24000.00	mg/kg TS
Kalium (K)	370.00	390.00	530.00	mg/kg TS
Kalsium (Ca)	2 200	3200.00	3000.00	mg/kg TS
Magnesium (Mg)	2 400	2800.00	3900.00	mg/kg TS
Mangan (Mn)	53.00	63.00	82.00	mg/kg TS
Natrium (Na)	170.00	430.00	510.00	mg/kg TS
Silisium (Si)	800.00	430.00	430.00	mg/kg TS
Tørrstoff	-	49.30	46.20	%
6:2 Fluortelomersulfonat (FTS)	566.00	277.00	232.00	µg/kg tv
8:2 Fluortelomersulfonat (FTS)	268.00	712.00	120.00	µg/kg tv
Perfluorbutansulfonat (PFBS)	< 6.5	< 3.5	< 3.6	µg/kg tv
Perfluorbutansyre (PFBA)	11.70	15.50	12.00	µg/kg tv
Perfluordekansyre (PFDA)	31.80	36.20	27.60	µg/kg tv
Perfluorheksansulfonat (PFHxS)	30.00	29.90	23.60	µg/kg tv
Perfluorheksansyre (PFHxA)	27.10	30.70	27.00	µg/kg tv
Perfluorheptansyre (PFHpA)	7.90	9.60	7.90	µg/kg tv
Perfluornonansyre (PFNA)	11.70	8.50	9.10	µg/kg tv
Perfluoroktansyre (PFOA)	17.40	21.70	16.60	µg/kg tv

Perfluoroktylsulfonat (PFOS)	5 350	4510.00	3950.00	µg/kg tv
Perfluorpentansyre (PFPeA)	30.90	40.90	33.00	µg/kg tv
Sum PFC forbindelser eksl. LOQ	6 350	5700.00	4450.00	µg/kg tv
Sum PFC forbindelser inkl. LOQ	6 360	5700.00	4460.00	µg/kg tv

Blank spaces (-) means no data.

Table 23: Element and PFC concentrations in soil in sample BP13.

Jord BP13	BP13-jord	BP13-J2	BP13-J3	Enhet
Total tørrstoff	23.00	23.00	24.00	%
Arsen (As)	3.30	2.80	2.40	mg/kg TS
Bly (Pb)	95.00	72.00	67.00	mg/kg TS
Kadmium (Cd)	0.55	0.37	0.35	mg/kg TS
Kobber (Cu)	38.00	14.00	21.00	mg/kg TS
Krom (Cr)	6.60	3.30	3.30	mg/kg TS
Nikkel (Ni)	8.10	<4.5	<4.1	mg/kg TS
Sink (Zn)	75.00	<45	<41	mg/kg TS
Kvikksølv (Hg)	0.23	0.25	0.50	mg/kg TS
Aluminium (Al)	2 200	1700.00	1600.00	mg/kg TS
Jern (Fe)	2 900	2100.00	2000.00	mg/kg TS
Kalium (K)	660.00	550.00	550.00	mg/kg TS
Kalsium (Ca)	4 000	3500.00	3200.00	mg/kg TS
Magnesium (Mg)	1 700	1300.00	1200.00	mg/kg TS
Mangan (Mn)	21.00	14.00	13.00	mg/kg TS
Natrium (Na)	1 100	1000.00	970.00	mg/kg TS
Silisium (Si)	1 300	750.00	710.00	mg/kg TS
Tørrstoff	-	23.10	22.60	%
6:2 Fluortelomersulfonat (FTS)	141.00	39.70	43.30	µg/kg tv
8:2 Fluortelomersulfonat (FTS)	30.00	9.00	14.20	µg/kg tv
Perfluorbutansulfonat (PFBS)	< 3.4	< 3.8	< 3.7	µg/kg tv
Perfluorbutansyre (PFBA)	11.90	10.60	12.50	µg/kg tv
Perfluordekansyre (PFDA)	6.10	4.60	5.20	µg/kg tv
Perfluorheksansulfonat (PFHxS)	5.90	4.80	5.10	µg/kg tv
Perfluorheksansyre (PFHxA)	23.90	20.80	23.90	µg/kg tv

Perfluorheptansyre (PFHpA)	3.70	3.10	3.40	µg/kg tv
Perfluornonansyre (PFNA)	4.30	3.30	3.50	µg/kg tv
Perfluoroktansyre (PFOA)	7.90	4.60	4.50	µg/kg tv
Perfluoroktylsulfonat (PFOS)	354.00	253.00	249.00	µg/kg tv
Perfluorpentansyre (PFPeA)	29.50	25.60	31.20	µg/kg tv
Sum PFC forbindelser eksl. LOQ	618.00	371.00	382.00	µg/kg tv
Sum PFC forbindelser inkl. LOQ	621.00	374.00	386.00	µg/kg tv

Blank spaces (-) means no data.

Table 24: Element and PFC concentrations in soil in sample KSU.

Jord KSU	KSU-Jord	KSU- J2	KSU- J3	Enhet
Total tørrstoff	22.00	18.00	20.00	%
Arsen (As)	<2.3	<2.9	<2.6	mg/kg TS
Bly (Pb)	3.60	5.80	5.80	mg/kg TS
Kadmium (Cd)	0.09	0.15	0.15	mg/kg TS
Kobber (Cu)	17.00	<4.5	<4.1	mg/kg TS
Krom (Cr)	5.90	7.60	3.80	mg/kg TS
Nikkel (Ni)	<4.6	9.70	5.90	mg/kg TS
Sink (Zn)	<46	<57	<52	mg/kg TS
Kvikksølv (Hg)	0.05	0.07	0.04	mg/kg TS
Aluminium (Al)	5 300	5700.00	4300.00	mg/kg TS
Jern (Fe)	3 100	3700.00	2900.00	mg/kg TS
Kalium (K)	630.00	750.00	500.00	mg/kg TS
Kalsium (Ca)	3 500	7000.00	12000.00	mg/kg TS
Magnesium (Mg)	1 400	1900.00	1400.00	mg/kg TS
Mangan (Mn)	77.00	110.00	89.00	mg/kg TS
Natrium (Na)	260.00	1100.00	840.00	mg/kg TS
Silisium (Si)	730.00	890.00	690.00	mg/kg TS
6:2 Fluortelomersulfonat (FTS)	< 3.1	< 3.7	< 3.6	µg/kg tv
8:2 Fluortelomersulfonat (FTS)	< 4.1	< 4.9	< 4.9	µg/kg tv
Perfluorbutansulfonat (PFBS)	35.20	31.80	26.00	µg/kg tv
Perfluorbutansyre (PFBA)	7.10	6.50	5.40	µg/kg tv
Perfluordekansyre (PFDA)	< 2.1	< 2.5	< 2.4	µg/kg tv

Perfluorheksansulfonat (PFHxS)	166.00	173.00	147.00	µg/kg tv
Perfluorheksansyre (PFHxA)	52.90	57.90	46.90	µg/kg tv
Perfluorheptansyre (PFHpA)	11.40	10.80	9.80	µg/kg tv
Perfluornonansyre (PFNA)	81.60	67.50	63.10	µg/kg tv
Perfluoroktansyre (PFOA)	26.50	19.00	15.80	µg/kg tv
Perfluoroktylsulfonat (PFOS)	89.10	120.00	133.00	µg/kg tv
Perfluorpentansyre (PFPeA)	11.00	9.30	7.60	µg/kg tv
Sum PFC forbindelser eksl. LOQ	481.00	496.00	455.00	µg/kg tv
Sum PFC forbindelser inkl. LOQ	490.00	502.00	466.00	µg/kg tv

10.2.2 Soil concentrations of PFCs

The average concentrations (µg/kg dw) from the analysis of PFCs in the different soil samples are shown in ***Table 25***. In the table the compound concentrations > LOQ are shaded. When considering all soil samples, it can be seen from the shaded areas that all the PFC compounds were quantified. The average concentrations (µg/kg dw) and standard deviations of PFCs in the different soil samples are shown in ***Table 26***. Blank spaces (-) for standard deviation are if the concentration is only over quantification limit in one or two of the samples in triplicate.

Table 25: Average soil concentrations (µg/kg dw) of the 12 PFCs analyzed for at the different sampled sites (< : lower than limit of quantification (LOQ)). Shaded areas show the PFCs concentrations > LOQ.

Concentrations of PFCs in soil (µg/kg dw)							
PFC (n=3)	**Ksand 30**	**Ksand 15 A**	**Ksand 15 B**	**BergenP7**	**BergenP3**	**BergenP13**	**Ksund**
6:2 FTS	4.90	< 3	< 3	28.3	358	74.7	< 3.7
8:2 FTS	9.00	< 4	< 4	12.6	367	17.7	< 4.9
PFBS	< 3	< 3	< 3	< 3.5	< 3.5	< 3.5	31.0
PFBA	< 2	< 2	< 2	11.4	13.1	11.7	6.33
PFDA	< 2	4.60	2.83	8.53	31.9	5.30	< 2.5

PFHxS	5.05	10.3	6.83	14.1	27.8	5.27	162
PFHxA	< 2	< 2	< 2	10.9	28.3	22.9	52.6
PFHpA	< 2	< 2	< 2	5.33	8.47	3.40	10.7
PFNA	< 2	4.10	3.20	8.87	9.77	3.70	70.7
PFOA	< 2	< 2	< 2	5.90	18.6	5.67	20.4
PFOS	714	471	255	776	4603	285	114
PFPeA	< 2	< 2	< 2	23.7	34.9	28.8	9.30
Sum PFC excl. LOQ	733	490	268	905	5501	464	477
Sum PFC incl. LOQ	750	510	285	909	5505	468	488

Table 26: Average (n=3, *Ksund n=2) concentrations (µg/kg) and standard deviations of the 12 PFCs analyzed for in the seven soil samples (< : lower than limit of quantification (LOQ)).

Mean concentrations and standard deviations of PFCs in soil (µg/kg)														
PFC	**KSA 30**		**KSA 15A**		**KSA 15B**		**BP7**		**BP3**		**BP13**		**KSUND**	
n = 3	Mean	Stdev.	Mean	Stdev.	Mean	Stdev.	Mean	Stdev.	Mean	Stdev.	Mean	Stdev.	Mean	Stdev.
6:2 FTS	4.90	-	< 3	-	< 3	-	28.3	6.66	358	181	74.7	57.5	< 3.7	-
8:2 FTS	9.00	-	< 4	-	< 4	-	12.6	-	367	308	17.7	10.9	< 4.9	-
PFBS	< 3	-	< 3	-	< 3	-	< 3.5	-	< 3.5	-	< 3.5	-	31.0	4.65
PFBA	< 2	-	< 2	-	< 2	-	11.4	1.61	13.1	2.11	11.7	0.97	6.33	0.86
PFDA	< 2	-	4.60	0.76	2.83	0.59	8.53	1.04	31.9	4.30	5.30	0.76	< 2.5	-
PFHxS	5.05	-	10.3	1.10	6.83	0.91	14.1	1.32	27.8	3.67	5.27	0.569	162	13.5
PFHxA	< 2	-	< 2	-	< 2	-	10.9	1.10	28.3	2.11	22.9	1.79	52.6	5.51
PFHpA	< 2	-	< 2	-	< 2	-	5.33	1.33	8.47	0.98	3.40	0.30	10.7	0.81
PFNA	< 2	-	4.10	0.89	3.20	0.95	8.87	0.80	9.77	1.70	3.70	0.53	70.7	9.66
PFOA	< 2	-	< 2	-	< 2	-	5.90	0.78	18.6	2.74	5.67	1.93	20.4	5.49
PFOS	714	191	471	72.1	255	71.3	776	41.8	4230	396	285	59.5	114	22.6
PFPeA	< 2	-	< 2	-	< 2	-	23.7	0.64	34.9	5.27	28.8	2.87	9.30	1.70

Blank spaces (-) for standard deviation are if the concentration is only over quantification limit in one or two of the samples in triplicate.

10.2.3 Water concentrations from batch experiments

Dissolved organic carbon (DOC), element composition, anions and PFC concentrations in water from the batch experiments with the different soil types are shown in ***Table 27*** (KSA30), ***Table 28*** (KSA15A), ***Table 29*** (KSA15B), ***Table 30*** (BP7), ***Table 31*** (BP3), ***Table 32*** (BP13) and ***Table 33***(KSU).

Table 27: Dissolved organic carbon (DOC), element concentrations, anions and PFC concentrations in water from batch experiments with soil sample KSA30.

Parameter	Ksand 30-1	Ksand 30-2	Ksand 30-3	Enhet
Klorid (Cl)	0.53	0.46	0.42	mg/l
Sulfat (SO4)	<0.25	<0.25	<0.25	mg/l
Fosfat (PO4-P)	36.00	39.00	31.00	µg/l
Nitrat (NO3-N)	110.00	94.00	97.00	µg/l
Løst organisk karbon (DOC)	7.60	7.30	7.40	mg/l
Arsen (As) ICP-MS	0.71	0.68	0.54	µg/l
Bly (Pb) ICP-MS	12.00	15.00	11.00	µg/l
Kadmium (Cd) ICP-MS	0.62	0.74	0.71	µg/l
Kobber (Cu) ICP-MS	26.00	29.00	24.00	µg/l
Krom (Cr) ICP-MS	8.60	12.00	8.70	µg/l
Kvikksølv (Hg)	0.00	0.00	0.00	µg/l
Nikkel (Ni) ICP-MS	0.74	0.96	0.64	µg/l
Sink (Zn) ICP-MS	8.80	8.90	6.20	µg/l
Aluminium (Al)	560.00	420.00	420.00	µg/l
Jern (Fe) ICP-MS	720.00	610.00	500.00	µg/l
Kalium (K)	1.90	2.00	2.10	mg/l
Kalsium (Ca)	0.81	0.71	0.69	mg/l
Magnesium (Mg)	0.11	0.11	0.11	mg/l
Mangan (Mn) ICP-MS	10.00	10.00	9.10	µg/l
Natrium (Na)	1.20	1.10	1.20	mg/l
Silisium (Si)	9000.00	8900.00	9600.00	µg/l
6:2 Fluortelomersulfonat (FTS)	0.40	0.30	0.40	µg/l
8:2 Fluortelomersulfonat (FTS)	0.60	0.60	0.70	µg/l

Perfluorbutansulfonat (PFBS)	< 0.2	< 0.2	< 0.2	µg/l
Perfluorbutansyre (PFBA)	0.30	0.30	0.30	µg/l
Perfluordekansyre (PFDA)	< 0.1	< 0.1	< 0.1	µg/l
Perfluorheksansulfonat (PFHxS)	0.30	0.30	0.40	µg/l
Perfluorheksansyre (PFHxA)	0.10	0.10	0.10	µg/l
Perfluorheptansyre (PFHpA)	< 0.1	< 0.1	< 0.1	µg/l
Perfluornonansyre (PFNA)	< 0.1	< 0.1	< 0.1	µg/l
Perfluoroktansyre (PFOA)	0.10	0.10	0.20	µg/l
Perfluoroktylsulfonat (PFOS)	55.60	51.60	51.20	µg/l
Perfluorpentansyre (PFPeA)	< 0.1	< 0.1	< 0.1	µg/l
Sum PFC forbindelser eksl. LOQ	57.40	53.50	53.20	µg/l
Sum PFC forbindelser inkl. LOQ	58.00	54.00	53.80	µg/l

Table 28: Dissolved organic carbon (DOC), element concentrations, anions and PFC concentrations in water from batch experiments with soil sample KSA15A.

Parameter	Ksand 15A- 1	Ksand 15A- 2	Ksand 15A- 3	Enhet
Klorid (Cl)	5.00	5.10	4.50	mg/l
Sulfat (SO4)	3.60	3.80	4.60	mg/l
Fosfat (PO4-P)	19.00	29.00	33.00	µg/l
Nitrat (NO3-N)	98.00	130.00	10.00	µg/l
Løst organisk karbon (DOC)	16.00	15.00	16.00	mg/l
Arsen (As) ICP-MS	1.60	1.50	1.60	µg/l
Bly (Pb) ICP-MS	33.00	30.00	35.00	µg/l
Kadmium (Cd) ICP-MS	0.45	0.24	0.18	µg/l
Kobber (Cu) ICP-MS	36.00	21.00	19.00	µg/l
Krom (Cr) ICP-MS	11.00	11.00	10.00	µg/l
Kvikksølv (Hg)	0.01	0.01	0.01	µg/l
Nikkel (Ni) ICP-MS	1.80	1.50	1.70	µg/l
Sink (Zn) ICP-MS	270.00	240.00	250.00	µg/l
Aluminium (Al)	3200.00	2800.00	3000.00	µg/l
Jern (Fe) ICP-MS	2700.00	2100.00	2200.00	µg/l
Kalium (K)	1.80	1.70	1.70	mg/l
Kalsium (Ca)	3.90	3.40	3.70	mg/l
Magnesium (Mg)	0.47	0.44	0.48	mg/l
Mangan (Mn) ICP-MS	43.00	43.00	57.00	µg/l
Natrium (Na)	4.00	4.00	4.00	mg/l
Silisium (Si)	6600.00	6300.00	6600.00	µg/l
6:2 Fluortelomersulfonat (FTS)	114.00	58.00	54.50	ng/l
8:2 Fluortelomersulfonat (FTS)	< 50	< 50	< 50	ng/l

Perfluorbutansulfonat (PFBS)	< 37.5	< 37.5	< 37.5	ng/l
Perfluorbutansyre (PFBA)	< 25	< 25	< 25	ng/l
Perfluordekansyre (PFDA)	124.00	124.00	135.00	ng/l
Perfluorheksansulfonat (PFHxS)	1270.00	1200.00	1320.00	ng/l
Perfluorheksansyre (PFHxA)	31.00	< 25	< 25	ng/l
Perfluorheptansyre (PFHpA)	< 25	< 25	< 25	ng/l
Perfluornonansyre (PFNA)	112.00	140.00	134.00	ng/l
Perfluoroktansyre (PFOA)	< 25	< 25	< 25	ng/l
Perfluoroktylsulfonat (PFOS)	19500.00	18500.00	19500.00	ng/l
Perfluorpentansyre (PFPeA)	< 25	< 25	< 25	ng/l
Sum PFC forbindelser eksl. LOQ	21200.00	20000.00	21200.00	ng/l
Sum PFC forbindelser inkl. LOQ	21400.00	20200.00	21400.00	ng/l

Table 29: Dissolved organic carbon (DOC), element concentrations, anions and PFC concentrations in water from batch experiments with soil sample KSA15B.

Parameter	Ksand 15B- 1	Ksand 15B- 2	Ksand 15B- 3	Enhet
Klorid (Cl)	1.30	1.40	4.90	mg/l
Sulfat (SO4)	<0.25	<0.25	<0.25	mg/l
Fosfat (PO4-P)	23.00	18.00	28.00	µg/l
Nitrat (NO3-N)	<5	<5	<5	µg/l
Løst organisk karbon (DOC)	12.00	11.00	18.00	mg/l
Arsen (As) ICP-MS	1.70	1.70	1.80	µg/l
Bly (Pb) ICP-MS	31.00	28.00	29.00	µg/l
Kadmium (Cd) ICP-MS	0.19	0.14	0.13	µg/l
Kobber (Cu) ICP-MS	16.00	21.00	19.00	µg/l
Krom (Cr) ICP-MS	11.00	11.00	11.00	µg/l
Kvikksølv (Hg)	0.01	0.01	0.01	µg/l
Nikkel (Ni) ICP-MS	1.50	1.40	1.50	µg/l
Sink (Zn) ICP-MS	230.00	230.00	240.00	µg/l
Aluminium (Al)	4800.00	4700.00	4500.00	µg/l
Jern (Fe) ICP-MS	4600.00	3400.00	3400.00	µg/l
Kalium (K)	1.30	1.30	1.30	mg/l
Kalsium (Ca)	2.70	2.60	2.60	mg/l
Magnesium (Mg)	0.40	0.38	0.40	mg/l
Mangan (Mn) ICP-MS	41.00	37.00	39.00	µg/l
Natrium (Na)	3.80	3.80	4.10	mg/l
Silisium (Si)	6500.00	6300.00	6400.00	µg/l
6:2 Fluortelomersulfonat (FTS)	21.20	23.80	15.20	ng/l

8:2 Fluortelomersulfonat (FTS)	< 20	< 20	< 20	ng/l
Perfluorbutansulfonat (PFBS)	< 15	< 15	< 15	ng/l
Perfluorbutansyre (PFBA)	< 10	< 10	< 10	ng/l
Perfluordekansyre (PFDA)	95.20	101.00	105.00	ng/l
Perfluorheksansulfonat (PFHxS)	746.00	790.00	866.00	ng/l
Perfluorheksansyre (PFHxA)	47.60	49.20	49.60	ng/l
Perfluorheptansyre (PFHpA)	< 10	< 10	< 10	ng/l
Perfluornonansyre (PFNA)	134.00	149.00	168.00	ng/l
Perfluoroktansyre (PFOA)	16.00	16.60	18.00	ng/l
Perfluoroktylsulfonat (PFOS)	11500.00	12200.00	12300.00	ng/l
Perfluorpentansyre (PFPeA)	< 10	< 10	< 10	ng/l
Sum PFC forbindelser eksl. LOQ	12600.00	13400.00	13500.00	ng/l
Sum PFC forbindelser inkl. LOQ	12600.00	13400.00	13600.00	ng/l

Table 30: Dissolved organic carbon (DOC), element concentrations, anions and PFC concentrations in water from batch experiments with soil sample BP7.

Parameter	BP7-1	BP7-2	BP7-3	Enhet
Klorid (Cl)	6.30	6.00	5.80	mg/l
Sulfat (SO4)	<0.25	<0.25	0.36	mg/l
Fosfat (PO4-P)	<2	<2	<2	µg/l
Nitrat (NO3-N)	3000.00	2900.00	2900.00	µg/l
Løst organisk karbon (DOC)	15.00	15.00	17.00	mg/l
Arsen (As) ICP-MS	0.53	0.53	0.49	µg/l
Bly (Pb) ICP-MS	15.00	14.00	14.00	µg/l
Kadmium (Cd) ICP-MS	0.13	0.11	0.12	µg/l
Kobber (Cu) ICP-MS	9.00	7.90	8.40	µg/l
Krom (Cr) ICP-MS	15.00	12.00	11.00	µg/l
Kvikksølv (Hg)	0.00	0.00	0.00	µg/l
Nikkel (Ni) ICP-MS	2.90	2.80	2.70	µg/l
Sink (Zn) ICP-MS	440.00	300.00	280.00	µg/l
Aluminium (Al)	2000.00	1700.00	1900.00	µg/l
Jern (Fe) ICP-MS	580.00	950.00	930.00	µg/l
Kalium (K)	2.30	2.30	2.30	mg/l
Kalsium (Ca)	3.30	3.30	3.20	mg/l
Magnesium (Mg)	1.30	1.30	1.30	mg/l
Mangan (Mn) ICP-MS	59.00	61.00	51.00	µg/l
Natrium (Na)	5.00	4.10	4.40	mg/l
Silisium (Si)	3000.00	2800.00	2900.00	µg/l

6:2 Fluortelomersulfonat (FTS)	1820.00	1780.00	1820.00	ng/l
8:2 Fluortelomersulfonat (FTS)	84.40	46.20	40.80	ng/l
Perfluorbutansulfonat (PFBS)	20.60	19.60	20.40	ng/l
Perfluorbutansyre (PFBA)	742.00	744.00	775.00	ng/l
Perfluordekansyre (PFDA)	22.40	24.20	25.80	ng/l
Perfluorheksansulfonat (PFHxS)	361.00	377.00	387.00	ng/l
Perfluorheksansyre (PFHxA)	740.00	754.00	772.00	ng/l
Perfluorheptansyre (PFHpA)	289.00	302.00	311.00	ng/l
Perfluornonansyre (PFNA)	125.00	133.00	145.00	ng/l
Perfluoroktansyre (PFOA)	181.00	193.00	198.00	ng/l
Perfluoroktylsulfonat (PFOS)	5260.00	4830.00	5110.00	ng/l
Perfluorpentansyre (PFPeA)	2010.00	2020.00	2080.00	ng/l
Sum PFC forbindelser eksl. LOQ	11700.00	11200.00	11700.00	ng/l
Sum PFC forbindelser inkl. LOQ	11700.00	11200.00	11700.00	ng/l

Table 31: Dissolved organic carbon (DOC), element concentrations, anions and PFC concentrations in water from batch experiments with soil sample BP3.

Parameter	BP3-1	BP3-2	BP3-3	Enhet
Klorid (Cl)	8.40	8.20	8.30	mg/l
Sulfat (SO4)	8.40	8.30	8.10	mg/l
Fosfat (PO4-P)	<2	<2	<2	µg/l
Nitrat (NO3-N)	86.00	110.00	130.00	µg/l
Løst organisk karbon (DOC)	25.00	22.00	23.00	mg/l
Arsen (As) ICP-MS	0.72	0.72	0.72	µg/l
Bly (Pb) ICP-MS	49.00	33.00	25.00	µg/l
Kadmium (Cd) ICP-MS	0.26	0.11	0.09	µg/l
Kobber (Cu) ICP-MS	18.00	11.00	13.00	µg/l
Krom (Cr) ICP-MS	14.00	14.00	14.00	µg/l
Kvikksølv (Hg)	0.01	0.01	0.01	µg/l
Nikkel (Ni) ICP-MS	1.50	1.40	1.20	µg/l
Sink (Zn) ICP-MS	390.00	380.00	380.00	µg/l
Aluminium (Al)	2000.00	2200.00	2200.00	µg/l
Jern (Fe) ICP-MS	1 300	1700.00	1600.00	µg/l
Kalium (K)	4.10	4.00	4.10	mg/l
Kalsium (Ca)	2.80	2.70	2.80	mg/l
Magnesium (Mg)	0.38	0.38	0.39	mg/l
Mangan (Mn) ICP-MS	11.00	9.80	10.00	µg/l
Natrium (Na)	6.40	6.30	6.70	mg/l

Silisium (Si)	2000.00	2000.00	2000.00	µg/l
6:2 Fluortelomersulfonat (FTS)	26600.00	28000.00	27800.00	ng/l
8:2 Fluortelomersulfonat (FTS)	482.00	515.00	550.00	ng/l
Perfluorbutansulfonat (PFBS)	100.00	104.00	109.00	ng/l
Perfluorbutansyre (PFBA)	918.00	961.00	976.00	ng/l
Perfluordekansyre (PFDA)	40.50	41.00	45.50	ng/l
Perfluorheksansulfonat (PFHxS)	846.00	926.00	916.00	ng/l
Perfluorheksansyre (PFHxA)	2180.00	2210.00	2240.00	ng/l
Perfluorheptansyre (PFHpA)	565.00	581.00	589.00	ng/l
Perfluornonansyre (PFNA)	29.50	66.00	106.00	ng/l
Perfluoroktansyre (PFOA)	268.00	262.00	261.00	ng/l
Perfluoroktylsulfonat (PFOS)	14000.00	14800.00	15500.00	ng/l
Perfluorpentansyre (PFPeA)	3060.00	3110.00	3140.00	ng/l
Sum PFC forbindelser eksl. LOQ	49200.00	51600.00	52200.00	ng/l
Sum PFC forbindelser inkl. LOQ	49200.00	51600.00	52200.00	ng/l

Table 32: Dissolved organic carbon (DOC), element concentrations, anions and PFC concentrations in water from batch experiments with soil sample BP13.

Parameter	BP13-1	BP13-2	BP13-3	Enhet
Klorid (Cl)	34.00	38.00	36.00	mg/l
Sulfat (SO4)	20.00	23.00	25.00	mg/l
Fosfat (PO4-P)	9700.00	7900.00	7500.00	µg/l
Nitrat (NO3-N)	.	.	.	µg/l
Løst organisk karbon (DOC)	110.00	170.00	120.00	mg/l
Arsen (As) ICP-MS	37.00	37.00	43.00	µg/l
Bly (Pb) ICP-MS	99.00	81.00	46.00	µg/l
Kadmium (Cd) ICP-MS	0.43	0.32	0.17	µg/l
Kobber (Cu) ICP-MS	100.00	160.00	120.00	µg/l
Krom (Cr) ICP-MS	11.00	12.00	14.00	µg/l
Kvikksølv (Hg)	0.03	0.03	0.02	µg/l
Nikkel (Ni) ICP-MS	3.30	4.00	3.00	µg/l
Sink (Zn) ICP-MS	650.00	840.00	620.00	µg/l
Aluminium (Al)	660.00	750.00	620.00	µg/l
Jern (Fe) ICP-MS	880.00	880.00	870.00	µg/l
Kalium (K)	14.00	15.00	14.00	mg/l
Kalsium (Ca)	3.70	4.00	2.80	mg/l
Magnesium (Mg)	1.90	2.20	1.50	mg/l
Mangan (Mn) ICP-MS	8.50	10.00	5.70	µg/l

Natrium (Na)	30.00	30.00	30.00	mg/l
Silisium (Si)	4400.00	4900.00	4900.00	µg/l
6:2 Fluortelomersulfonat (FTS)	4150.00	2950.00	3030.00	ng/l
8:2 Fluortelomersulfonat (FTS)	68.50	55.00	57.50	ng/l
Perfluorbutansulfonat (PFBS)	< 37.5	< 37.5	< 37.5	ng/l
Perfluorbutansyre (PFBA)	1020.00	1040.00	1070.00	ng/l
Perfluordekansyre (PFDA)	< 25	< 25	< 25	ng/l
Perfluorheksansulfonat (PFHxS)	93.00	81.00	87.50	ng/l
Perfluorheksansyre (PFHxA)	1650.00	1550.00	1570.00	ng/l
Perfluorheptansyre (PFHpA)	231.00	146.00	162.00	ng/l
Perfluornonansyre (PFNA)	39.50	26.50	27.00	ng/l
Perfluoroktansyre (PFOA)	115.00	92.50	102.00	ng/l
Perfluoroktylsulfonat (PFOS)	1050.00	662.00	863.00	ng/l
Perfluorpentansyre (PFPeA)	2500.00	2510.00	2460.00	ng/l
Sum PFC forbindelser eksl. LOQ	10900.00	9110.00	9430.00	ng/l
Sum PFC forbindelser inkl. LOQ	11000.00	9170.00	9490.00	ng/l

Blank spaces (-) means no data.

Table 33: Dissolved organic carbon (DOC), element concentrations, anions and PFC concentrations in water from batch experiments with soil sample KSU.

Parameter	KSU-1	KSU-2	Enhet
Klorid (Cl)	33.00	27.00	mg/l
Sulfat (SO4)	41.00	38.00	mg/l
Fosfat (PO4-P)	84.00	70.00	µg/l
Nitrat (NO3-N)	.	.	µg/l
Løst organisk karbon (DOC)	240.00	180.00	mg/l
Arsen (As) ICP-MS	2.00	1.70	µg/l
Bly (Pb) ICP-MS	8.90	91.00	µg/l
Kadmium (Cd) ICP-MS	0.08	0.69	µg/l
Kobber (Cu) ICP-MS	39.00	61.00	µg/l
Krom (Cr) ICP-MS	11.00	6.30	µg/l
Kvikksølv (Hg)	0.00	0.00	µg/l
Nikkel (Ni) ICP-MS	8.50	8.90	µg/l
Sink (Zn) ICP-MS	450.00	950.00	µg/l
Aluminium (Al)	2200.00	1900.00	µg/l
Jern (Fe) ICP-MS	820.00	640.00	µg/l
Kalium (K)	8.10	8.30	mg/l

Kalsium (Ca)	6.40	6.00	mg/l
Magnesium (Mg)	1.50	1.10	mg/l
Mangan (Mn) ICP-MS	65.00	52.00	µg/l
Natrium (Na)	18.00	15.00	mg/l
Silisium (Si)	12000.00	11000.00	µg/l
6:2 Fluortelomersulfonat (FTS)	< 37.5	68.00	ng/l
8:2 Fluortelomersulfonat (FTS)	< 50	< 50	ng/l
Perfluorbutansulfonat (PFBS)	4260.00	4090.00	ng/l
Perfluorbutansyre (PFBA)	904.00	822.00	ng/l
Perfluordekansyre (PFDA)	< 25	< 25	ng/l
Perfluorheksansulfonat (PFHxS)	10300.00	10600.00	ng/l
Perfluorheksansyre (PFHxA)	6540.00	5940.00	ng/l
Perfluorheptansyre (PFHpA)	978.00	950.00	ng/l
Perfluornonansyre (PFNA)	1210.00	1270.00	ng/l
Perfluoroktansyre (PFOA)	1130.00	1170.00	ng/l
Perfluoroktylsulfonat (PFOS)	398.00	732.00	ng/l
Perfluorpentansyre (PFPeA)	1460.00	1330.00	ng/l
Sum PFC forbindelser eksl. LOQ	27200.00	26900.00	ng/l
Sum PFC forbindelser inkl. LOQ	27300.00	27000.00	ng/l

Blank spaces (-) means no data.

10.2.4 Average water concentrations of PFCs from batch experiments

The average PFC concentrations (µg/l) in the water samples from batch experiments are shown in ***Table 34***. In the table the compound concentrations > LOQ are shaded, compared to soil samples there are more compounds quantified in the water samples. The ***Table 35*** is including standard deviations of the triplicates at each site. Blank spaces (-) for standard deviation are if the concentration is only over quantification limit in one or two of the samples in triplicate.

Table 34: Average (n=3, * Ksund n=2) concentrations (µg/l) of the 12 PFCs analyzed for in filtered water samples of batch experiments (< : lower than limit of quantification (LOQ)).

Concentrations of PFCs in water (µg/l)							
PFC (n = 3)	**Ksand 30**	**Ksand 15 A**	**Ksand 15 B**	**BergenP7**	**BergenP3**	**BergenP13**	**Ksund***
6:2 FTS	0.37	0.08	0.02	1.81	27.5	3.38	0.068
8:2 FTS	0.63	< 0.05	< 0.02	0.06	0.52	0.06	< 0.05
PFBS	< 0.002	< 0.04	< 0.015	0.02	0.10	< 0.04	4.18
PFBA	0.30	< 0.03	< 0.01	0.75	0.95	1.04	0.86
PFDA	< 0.001	0.13	0.10	0.02	0.04	< 0.03	< 0.03
PFHxS	0.33	1.26	0.80	0.38	0.90	0.09	10.45
PFHxA	0.10	0.03	0.05	0.76	2.21	1.59	6.24
PFHpA	< 0.001	< 0.03	< 0.01	0.30	0.58	0.18	0.96
PFNA	< 0.001	0.129	0.150	0.13	0.07	0.03	1.24
PFOA	0.13	< 0.03	0.017	0.19	0.26	0.10	1.15
PFOS	52.8	19.2	12.0	5.07	14.8	0.86	0.57
PFPeA	< 0.001	< 0.03	< 0.01	2.04	3.10	2.49	1.40
Sum PFC excl. LOQ	54.7	20.8	13.2	11.5	51.0	9.82	27.1
Sum PFC incl. LOQ	55.3	21.0	13.2	11.5	51.0	9.89	27.2

Table 35: Average (n=3, *Ksund n=2) concentrations (µg/l) and standard deviations of the 12 PFCs analyzed for in filtered water samples of batch experiments (< : lower than limit of quantification (LOQ)).

Mean concentrations and standard deviations of PFCs in water (µg/l)														
PFC	**Ksand 30**		**Ksand 15 A**		**Ksand 15 B**		**BergenP7**		**BergenP3**		**BergenP13**		**Ksund***	
n = 3	µ	σ	µ	σ	µ	σ	µ	σ	µ	σ	µ	σ	µ	σ
6:2 FTS	0.37	0.06	0.08	0.03	0.02	0.004	1.81	0.02	27.5	0.76	3.38	0.67	0.068	-
8:2 FTS	0.63	0.06	< 0.05	-	< 0.02	-	0.06	0.02	0.52	0.03	0.06	0.007	< 0.05	-
PFBS	< 0.002	-	< 0.04	-	< 0.015	-	0.02	0.001	0.10	0.005	< 0.04	-	4.18	0.12
PFBA	0.30	0	< 0.03	-	< 0.01	-	0.75	0.02	0.95	0.03	1.04	0.03	0.86	0.06
PFDA	< 0.001	-	0.13	0.006	0.10	0.005	0.02	0.002	0.04	0.003	< 25	-	< 0.03	-
PFHxS	0.33	0.06	1.26	0.06	0.80	0.06	0.38	0.01	0.90	0.04	0.09	0.006	10.45	0.21
PFHxA	0.10	1.7e-17	0.03	-	0.05	0.001	0.76	0.02	2.21	0.03	1.59	0.05	6.24	0.42
PFHpA	< 0.001	-	< 0.03	-	< 0.01	-	0.30	0.01	0.58	0.01	0.18	0.05	0.96	0.02
PFNA	< 0.001	-	0.129	0.02	0.150	0.02	0.13	0.01	0.07	0.04	0.03	0.007	1.24	0.04
PFOA	0.13	0.06	< 0.03	-	0.017	0.001	0.19	0.01	0.26	0.004	0.10	0.01	1.15	0.03
PFOS	52.8	2.43	19.2	0.58	12.0	0.44	5.07	0.22	14.8	0.75	0.86	0.19	0.57	0.24
PFPeA	< 0.001	-	< 0.03	-	< 0.01	-	2.04	0.04	3.10	0.04	2.49	0.03	1.40	0.09

Blank spaces (-) for standard deviation are if the concentration is only over quantification limit in one or two of the samples in triplicate.

10.2.5 Calculated log K_d, K_{oc} and log K_{oc}

The calculated values for log K_d, K_{oc} and log K_{oc} based on the TOC content in the various soil samples from batch experiments are in ***Table 36***, ***Table 37*** and ***Table 38***.

. For compounds only quantified in either the soil or water sample, the LOQ value was used for estimation of K_d as described in section 4. Methods. Blank spaces (-) are sites where compounds were not quantified in soil or water.

Table 36: Calculated values of log K_d for the PFC compounds quantified in soil and water samples of the batch experiments.

Log Kd	**KSA 30***	**KSA 15A**	**KSA 15B**	**BP7**	**BP3**	**BP13**	**KSUND**
PFBA (C4)	-	-	-	1.18	1.14	1.05	0.866
PFBS (C4)	-	-	-	-	-	-	0.871
PFPeA (C5)	-	-	-	1.07	1.05	1.06	0.824
PFHxA (C6)	-	-	-	1.16	1.11	1.16	0.926
PFHxS (C6)	1.18	0.910	0.931	1.58	1.49	1.78	1.19
PFHpA (C7)	-	-	-	1.25	1.17	1.28	1.04
6:2 FTS (C8)	1.13	-	-	1.20	1.12	1.34	-
PFOA (C8)	-	-	-	1.49	1.85	1.74	1.25
PFOS (C8)	1.13	1.39	1.33	2.18	2.49	2.52	2.30
PFNA (C9)	-	1.50	1.33	1.82	2.16	2.08	1.76
8:2 FTS (C10)	1.15	-	-	2.34	2.85	2.47	-
PFDA (C10)	-	1.56	1.45	2.55	2.88	-	-

* For site KSA 30 polysulfone filters was used, for all other sites glass fiber filters (GF/C) was used.

Table 37: Calculated values of K_{oc} for the PFC compounds quantified in soil and water samples of the batch experiments.

Koc	**KSA 30***	**KSA 15A**	**KSA 15B**	**BP7**	**BP3**	**BP13**	**KSUND**
PFBA (C4)	-	-	-	177	144	24.5	17.0
PFBS (C4)	-	-	-	-	-	-	17.2
PFPeA (C5)	-	-	-	136	118	25.3	15.4
PFHxA (C6)	-	-	-	169	135	31.5	19.5
PFHxS (C6)	7321	490	626	441	327	132	35.9
PFHpA (C7)	-	-	-	208	154	41.4	25.6
6:2 FTS (C8)	6457	-	-	183	137	48.4	-
PFOA (C8)	-	-	-	362	741	120	41.2
PFOS (C8)	6534	1482	1557	1791	3279	728	468
PFNA (C9)	-	1922	1562	772	1530	261	132
8:2 FTS (C10)	6867	-	-	2570	7480	643	-
PFDA (C10)	-	2173	2070	4137	7918	-	-

* For site KSA 30 polysulfone filters was used, for all other sites glass fiber filters (GF/C) was used.

Table 38: Calculated values of log K_{oc} for the PFC compounds quantified in soil and water samples of the batch experiments.

log Koc	**KSA 30**	**KSA 15A**	**KSA 15B**	**BP7**	**BP3**	**BP13**	**KSUND**
PFBA (C4)	-	-	-	2.25	2.16	1.39	1.23
PFBS (C4)	-	-	-	-	-	-	1.24
PFPeA (C5)	-	-	-	2.13	2.07	1.40	1.19
PFHxA (C6)	-	-	-	2.23	2.13	1.50	1.29
PFHxS (C6)	3.86	2.69	2.80	2.64	2.51	2.12	1.56
PFHpA (C7)	-	-	-	2.32	2.19	1.62	1.41
6:2 FTS (C8)	3.81	-	-	2.26	2.14	1.68	-
PFOA (C8)	--	-	-	2.56	2.87	2.08	1.61
PFOS (C8)	3.82	3.17	3.19	3.25	3.52	2.86	2.67
PFNA (C9)	-	3.28	3.19	2.89	3.18	2.42	2.12
8:2 FTS (C10)	3.84	-	-	3.41	3.87	2.81	-
PFDA (C10)	-	3.34	3.32	3.62	3.90	-	-

* For site KSA 30 polysulfone filters was used, for all other sites glass fiber filters (GF/C) was used.

Table 39 show the calculated difference in log Koc values for each added CF_2 to the carbon chain of perfluorocarboxylic acid (PFCA) compounds.

Table 39: Calculated difference of log Koc for each added CF_2 moiety of a PFCA molecule.

log Koc	BP7	BP3	BP13	KSUND	Δ BP7	Δ BP3	Δ BP13	Δ KSUND
PFBA (C4)	2.25	2.16	1.39	1.23	-	-	-	-
PFPeA (C5)	2.13	2.07	1.41	1.19	-0.1	-0.1	0.03	-0.04
PFHxA (C6)	2.23	2.13	1.50	1.29	0.1	0.1	0.1	0.1
PFHpA (C7)	2.32	2.19	1.62	1.41	0.1	0.1	0.1	0.1
PFOA (C8)	2.56	2.87	2.08	1.61	0.2	0.7	0.5	0.2
PFNA (C9)	2.89	3.18	2.42	2.12	0.3	0.3	0.3	0.5
PFDA (C10)	3.62	3.90	-	-	0.7	0.7	-	-

10.2.6 Correlation between K_d and K_{oc}

There was in general not found any clear linear correlations between K_d and K_{oc}, except for the compound PFDA (see ***Figure 76***). In the plot it can be seen that among the sites were K_d for PFDA could be calculated, BP3 has the highest TOC and the highest sorption of the compound. BP7 has the second highest TOC and sorption of PFDA. Both the sites KSA 15 A and B has very low TOC level. For PFDA the sorption of the compound increases even when normalizing for the highest soil organic carbon contents. This indicates that sorption is strongly dependent on the soil characteristics. If we assume that it is the soil organic carbon content that controls the sorption of PFDA, the concentration of this compound in water is then likely to be highest at sites where the concentration of organic material in soil is low.

When normalizing K_d for the fraction of organic carbon in a soil with very low organic carbon content (like KSA 30) K_{oc} becomes relatively high. Calculated K_{oc} values for the sulfonic compounds found at Ksand 30 are in the range 6457-7321 l/kg. By calculating the K_{oc} values based on the TOC content in the soil, it cannot be explained if the strong sorption

of a compound is to mineral surfaces or organic carbon. For PFOS in ***Figure 76*** no linear correlation between K_d and K_{oc} was observed.

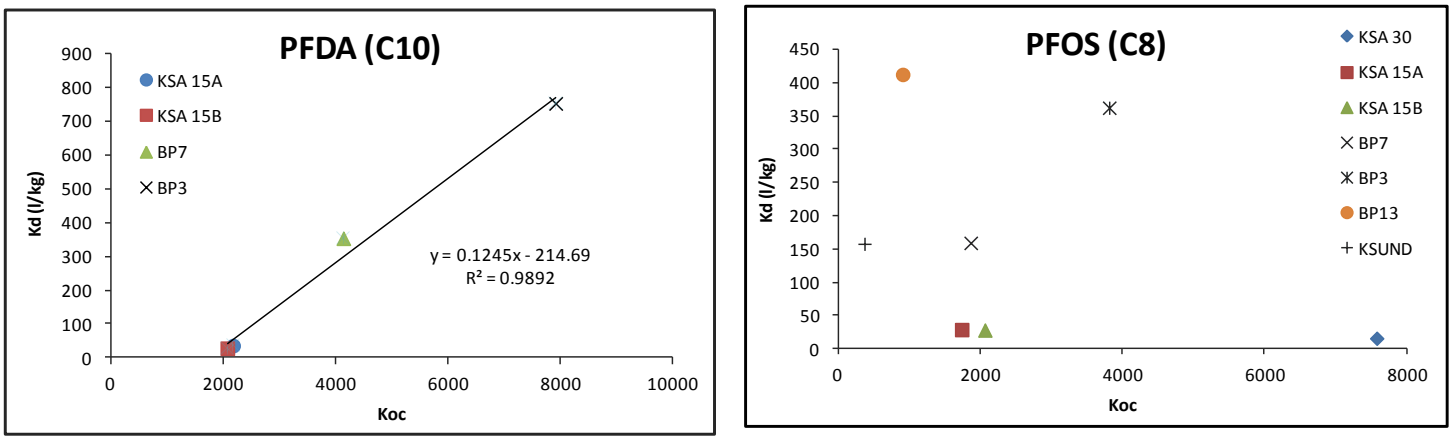

Figure 76: Linear correlation between K_d and Koc for the compound PFDA (left). No linear correlation between K_d and Koc for the compound PFOS (right).

10.3 Appendix C

10.3.1 Water concentrations in leachate of columns

Dissolved organic carbon (DOC), element composition, anions and PFC concentrations in water at each sampled L/S ratio of the column experiments are shown in ***Table 40***, ***Table 41***,***Table 42***, ***Table 43***, ***Table 44*** and ***Table 45***. In water samples of L/S ratio 2 from Kristiansand columns LOQ for the compounds are very high (< 500 - < 1500 ng/l), compared to samples of the other L/S ratios (< 5 - < 75 ng/l).

Table 40: Dissolved organic carbon (DOC), element concentrations, anions and PFC concentrations in water at each sampled L/S ratio of column KSA30-A.

K.sand 30 A	L/S 2	L/S 4	L/S 6	L/S 8	L/S 10	Units
Date of sampling	2012-10-15	2012-10-22	2012-10-31	2012-11-05	2012-11-12	
Time of sampling	5:28 PM	4:10 PM	8:39 AM	12:50 PM	7:34 AM	
Weight of water	6350	6415	6405	6474	7373	g
Diff from estimated L/S ratio 2	-714	-649	-659	-590	309	g
Temperature	14.5	14.5	18	14.5	12	°C
pH	7.47	7.66	7.07	7.22	7.67	
Conductivity	45.9	35.7	11.8	7.6	6.9	µs/cm
Klorid (Cl)	0.73	0.42	0.39	0.28	0.26	mg/l
Sulfat (SO4)	<0.25	<0.25	<0.25	<0.25	<0.25	mg/l
Fosfat (PO4-P)	51.00	37.00	34.00	31.00	26.00	µg/l
Nitrat (NO3-N)	640.00	29.00	35.00	29.00	26.00	µg/l
Løst organisk karbon (DOC)	10.00	4.50	3.70	2.70	2.50	mg/l
Bly (Pb), filtrert ICP-MS	1.90	0.43	0.34	0.25	0.23	µg/l
Kadmium (Cd), filtrert ICP-MS	0.08	0.04	0.04	0.03	0.02	µg/l
Kobber (Cu), filtrert ICP-MS	4.20	2.50	1.60	1.20	0.96	µg/l
Krom (Cr), filtrert ICP-MS	0.87	0.38	0.34	0.28	0.19	µg/l
Kvikksølv (Hg), filtrert	<0.002	<0.002	<0.002	<0.002	<0.002	µg/l
Nikkel (Ni), filtrert ICP-MS	2.10	1.20	0.76	0.54	0.82	µg/l
Sink (Zn), filtrert ICP-MS	4.30	1.90	2.50	1.40	1.20	µg/l
Aluminium (Al), filtrert	440.00	170.00	140.00	110.00	87.00	µg/l
Jern (Fe), filtrert ICP-MS	820.00	190.00	160.00	110.00	83.00	µg/l
Kalium (K), filtrert	4.00	2.00	1.60	1.30	1.00	mg/l
Kalsium (Ca), filtrert	6.00	1.70	0.70	0.44	0.48	mg/l
Magnesium (Mg), filtrert	0.08	0.03	0.03	0.03	0.03	mg/l
Mangan (Mn), filtrert ICP-MS	7.80	1.40	1.20	0.94	0.95	µg/l
Natrium (Na), filtrert	1.30	0.32	0.18	0.10	0.07	mg/l
Silisium (Si), filtrert	870.00	250.00	210.00	140.00	100.00	µg/l
Arsen (As), filtrert ICP-MS	0.73	0.34	0.27	0.28	0.23	µg/l
6:2 FTS	4610.00	370.00	249.00	128.00	108.00	ng/l
8:2 FTS	1040.00	223.00	< 100	< 100	< 100	ng/l
PFBS	< 750	< 75	< 75	< 75	< 75	ng/l
PFBA	< 500	< 50	< 50	< 50	< 50	ng/l
PFDA	< 500	< 50	< 50	< 50	< 50	ng/l

PFHxS	1160.00	< 75	< 75	< 75	< 75	ng/l
PFHxA	< 500	< 50	< 50	< 50	< 50	ng/l
PFHpA	< 500	< 50	< 50	< 50	< 50	ng/l
PFNA	< 500	< 50	< 50	< 50	< 50	ng/l
PFOA	< 500	< 50	< 50	< 50	< 50	ng/l
PFOS	170000.00	30400.00	14200.00	8640.00	4940.00	ng/l
PFPeA	690.00	< 50	< 50	< 50	< 50	ng/l
Sum PFC exsl. LOQ	177000.00	31000.00	14400.00	8760.00	5050.00	ng/l
Sum PFC incl. LOQ	181000.00	31500.00	15000.00	9360.00	5650.00	ng/l

Table 41: Dissolved organic carbon (DOC), element concentrations, anions and PFC concentrations in water at each sampled L/S ratio of column KSA30-B.

K.sand 30 B	**L/S 2**	**L/S 4**	**L/S 6**	**L/S 8**	**L/S 10**	**Units**
Date of sampling	2012-10-15	2012-10-22	2012-10-31	2012-11-06	2012-11-13	
Time of sampling	4:26 PM	4:27 PM	8:24 AM	7:56 AM	8:43 AM	
Weight of water	6461	6424	6785	6569	6423	g
Diff from estimated L/S ratio 2	600	563	924	708	562	g
Temperature	12.6	15.4	14.9	14.7	12.8	°C
pH	7.49	7.77	7.5	7.49	7.8	
Conductivity	40	12.1	8.4	7.8	7	µs/cm
Klorid (Cl)	0.69	0.40	0.36	0.35	0.25	mg/l
Sulfat (SO4)	<0.25	<0.25	<0.25	<0.25	<0.25	mg/l
Fosfat (PO4-P)	28.00	24.00	19.00	16.00	16.00	µg/l
Nitrat (NO3-N)	460.00	18.00	30.00	23.00	18.00	µg/l
Løst organisk karbon (DOC)	10.00	4.00	3.40	2.80	2.90	mg/l
Bly (Pb), filtrert ICP-MS	0.95	0.29	0.17	0.12	0.14	µg/l
Kadmium (Cd), filtrert ICP-MS	0.04	0.01	0.01	0.01	0.01	µg/l
Kobber (Cu), filtrert ICP-MS	2.60	1.50	0.88	0.64	0.54	µg/l
Krom (Cr), filtrert ICP-MS	0.84	0.38	0.32	0.19	0.36	µg/l
Kvikksølv (Hg), filtrert	0.00	<0.002	<0.002	<0.002	<0.002	µg/l
Nikkel (Ni), filtrert ICP-MS	1.50	0.89	0.79	0.41	0.47	µg/l
Sink (Zn), filtrert ICP-MS	7.70	4.00	2.20	1.60	1.90	µg/l
Aluminium (Al), filtrert	440.00	180.00	140.00	99.00	91.00	µg/l
Jern (Fe), filtrert ICP-MS	510.00	120.00	85.00	54.00	52.00	µg/l
Kalium (K), filtrert	3.30	1.70	1.50	1.10	0.93	mg/l
Kalsium (Ca), filtrert	1.30	0.48	0.52	0.48	0.52	mg/l
Magnesium (Mg), filtrert	0.09	0.03	0.04	0.04	0.04	mg/l

Mangan (Mn), filtrert ICP-MS	5.90	1.20	1.10	0.72	0.79	µg/l
Natrium (Na), filtrert	1.10	0.30	0.18	0.10	0.07	mg/l
Silisium (Si), filtrert	740.00	230.00	190.00	110.00	97.00	µg/l
Arsen (As), filtrert ICP-MS	0.40	0.23	0.22	0.16	0.17	µg/l
6:2 FTS	< 1,500	226.00	111.00	< 75	71.70	ng/l
8:2 FTS	< 2,000	172.00	< 100	< 100	24.50	ng/l
PFBS	< 1,500	< 75	< 75	< 75	< 7.5	ng/l
PFBA	< 1,000	< 50	< 50	< 50	18.70	ng/l
PFDA	< 1,000	< 50	< 50	< 50	6.00	ng/l
PFHxS	< 1,500	133.00	< 75	< 75	30.60	ng/l
PFHxA	< 1,000	< 50	< 50	< 50	10.40	ng/l
PFHpA	< 1,000	< 50	< 50	< 50	< 5	ng/l
PFNA	< 1,000	< 50	< 50	< 50	< 5	ng/l
PFOA	< 1,000	< 50	< 50	< 50	7.60	ng/l
PFOS	277000.00	36700.00	18600.00	9790.00	6110.00	ng/l
PFPeA	< 1,000	< 50	< 50	< 50	17.00	ng/l
Sum PFC exsl. LOQ	277000.00	37200.00	18700.00	9790.00	6290.00	ng/l
Sum PFC incl. LOQ	290000.00	37600.00	19300.00	10500.00	6310.00	ng/l

Table 42: Dissolved organic carbon (DOC), element concentrations, anions and PFC concentrations in water at each sampled L/S ratio of column BP3-A.

B P3 A	**L/S 2**	**L/S 4**	**L/S 6**	**L/S 8**	**L/S 10**	**Units**
Date of sampling	2012-10-15	2012-10-22	2012-10-29	2012-11-05	2012-11-13	
Time of sampling	5:09 PM	5:05 PM	11:33 AM	10:53 AM	9:18 AM	
Weight of water	2159	2137	2151	2165	2158	g
Diff from estimated L/S ratio 2	-2	-24	-10	4	-3	g
Temperature	13.3	10.6	17	13.3	13.4	°C
pH	7.2	6.94	6.79	6.96	7.02	
Conductivity (us/cm)	127.7	71.2	62	51.5	48.4	µs/cm
Klorid (Cl)	9.80	2.40	3.00	2.40	3.50	mg/l
Sulfat (SO4)	23.00	8.10	<0.25	<0.25	<0.25	mg/l
Fosfat (PO4-P)	7.60	4.30	<2	<2	<2	µg/l
Nitrat (NO3-N)	1900.00	93.00	19.00	<5	<5	µg/l
Løst organisk karbon (DOC)	20.00	31.00	38.00	37.00	38.00	mg/l
Bly (Pb), filtrert ICP-MS	1.20	2.30	2.40	2.80	4.20	µg/l
Kadmium (Cd), filtrert ICP-MS	0.10	0.09	0.10	0.09	0.11	µg/l
Kobber (Cu), filtrert ICP-MS	9.40	29.00	16.00	11.00	15.00	µg/l
Krom (Cr), filtrert ICP-MS	2.00	2.90	3.50	3.50	4.90	µg/l
Kvikksølv (Hg), filtrert	0.01	0.03	0.03	0.01	0.02	µg/l
Nikkel (Ni), filtrert ICP-MS	1.40	1.70	2.50	2.30	2.60	µg/l
Sink (Zn), filtrert ICP-MS	36.00	9.30	14.00	32.00	270.00	µg/l
Aluminium (Al), filtrert	740.00	1400.00	2100.00	2200.00	2100.00	µg/l

Jern (Fe), filtrert ICP-MS	470.00	660.00	810.00	1500.00	1300.00	µg/l
Kalium (K), filtrert	8.30	5.90	5.20	4.90	4.80	mg/l
Kalsium (Ca), filtrert	7.00	4.10	3.60	3.50	2.80	mg/l
Magnesium (Mg), filtrert	0.90	0.48	0.41	0.39	0.35	mg/l
Mangan (Mn), filtrert ICP-MS	10.00	16.00	16.00	14.00	21.00	µg/l
Natrium (Na), filtrert	9.10	5.60	4.00	2.80	3.10	mg/l
Silisium (Si), filtrert	2600.00	1500.00	1200.00	1000.00	1200.00	µg/l
Arsen (As), filtrert ICP-MS	0.56	0.91	1.30	1.50	2.30	µg/l
6:2 Fluortelomersulfonat (FTS)	45900.00	42900.00	16500.00	5640.00	3340.00	ng/l
8:2 Fluortelomersulfonat (FTS)	476.00	699.00	683.00	687.00	680.00	ng/l
Perfluorbutansulfonat (PFBS)	354.00	< 75	< 75	< 75	< 75	ng/l
Perfluorbutansyre (PFBA)	4880.00	280.00	< 50	< 50	< 50	ng/l
Perfluordekansyre (PFDA)	69.00	102.00	107.00	113.00	115.00	ng/l
Perfluorheksansulfonat (PFHxS)	1630.00	1610.00	678.00	253.00	141.00	ng/l
Perfluorheksansyre (PFHxA)	8990.00	1360.00	246.00	125.00	108.00	ng/l
Perfluorheptansyre (PFHpA)	2580.00	972.00	177.00	83.00	66.00	ng/l
Perfluornonansyre (PFNA)	230.00	322.00	356.00	384.00	362.00	ng/l
Perfluoroktansyre (PFOA)	1510.00	1800.00	1080.00	465.00	283.00	ng/l
Perfluoroktylsulfonat (PFOS)	16900.00	26300.00	28000.00	29800.00	27800.00	ng/l
Perfluorpentansyre (PFPeA)	15200.00	1300.00	145.00	77.00	62.00	ng/l
Sum PFC forbindelser eksl. LOQ	98700.00	77600.00	47900.00	37600.00	32900.00	ng/l
Sum PFC forbindelser inkl. LOQ	98700.00	77700.00	48000.00	37700.00	33100.00	ng/l

Table 43: Dissolved organic carbon (DOC), element concentrations, anions and PFC concentrations in water at each sampled L/S ratio of column BP3-B.

B P3 B	**L/S 2**	**L/S 4**	**L/S 6**	**L/S 8**	**L/S 10**	**Units**
Date of sampling	2012-10-15	2012-10-22	2012-10-29	2012-11-05	2012-11-12	
Time of sampling	4:58 PM	9:00 AM	11:24 AM	3:30 PM	12:22 PM	
Weight of water (g)	2158	2160	2154	2183	2164	g
Diff from estimated L/S ratio 2	32	34	28	57	38	g
Temperature	11	12.9	15.9	13.4	13.2	°C
pH	7.76	7.86	7.51	7.14	7.15	
Conductivity (us/cm)	164.9	98.8	86.3	67.5	56.9	µs/cm
Klorid (Cl)	9.50	2.30	2.90	2.80	3.00	mg/l
Sulfat (SO4)	24.00	15.00	<0.25	<0.25	<0.25	mg/l
Fosfat (PO4-P)	13.00	3.20	<2	<2	<2	µg/l
Nitrat (NO3-N)	2400.00	300.00	83.00	14.00	<5	µg/l
Løst organisk karbon (DOC)	23.00	34.00	39.00	39.00	38.00	mg/l
Bly (Pb), filtrert ICP-MS	3.20	1.70	5.00	4.50	4.20	µg/l

Kadmium (Cd), filtrert ICP-MS	0.08	0.06	0.12	0.10	0.08	µg/l
Kobber (Cu), filtrert ICP-MS	5.10	18.00	9.80	5.70	4.90	µg/l
Krom (Cr), filtrert ICP-MS	2.60	2.70	3.90	4.00	4.50	µg/l
Kvikksølv (Hg), filtrert	0.08	0.03	0.03	0.02	0.02	µg/l
Nikkel (Ni), filtrert ICP-MS	1.60	1.80	3.30	3.10	2.80	µg/l
Sink (Zn), filtrert ICP-MS	19.00	8.00	150.00	200.00	200.00	µg/l
Aluminium (Al), filtrert	1000.00	1600.00	2200.00	2100.00	2000.00	µg/l
Jern (Fe), filtrert ICP-MS	1100.00	690.00	1900.00	2300.00	2300.00	µg/l
Kalium (K), filtrert	7.80	5.60	4.30	4.60	3.90	mg/l
Kalsium (Ca), filtrert	18.00	13.00	11.00	8.20	5.40	mg/l
Magnesium (Mg), filtrert	0.91	0.47	0.40	0.39	0.39	mg/l
Mangan (Mn), filtrert ICP-MS	18.00	12.00	14.00	14.00	16.00	µg/l
Natrium (Na), filtrert	8.50	5.10	6.20	3.40	4.50	mg/l
Silisium (Si), filtrert	2700.00	1600.00	1400.00	1100.00	1000.00	µg/l
Arsen (As), filtrert ICP-MS	0.60	0.82	1.30	1.50	1.60	µg/l
6:2 Fluortelomersulfonat (FTS)	40700.00	38900.00	14400.00	5600.00	2990.00	ng/l
8:2 Fluortelomersulfonat (FTS)	435.00	604.00	545.00	555.00	552.00	ng/l
Perfluorbutansulfonat (PFBS)	357.00	< 75	< 75	< 75	< 75	ng/l
Perfluorbutansyre (PFBA)	4840.00	439.00	141.00	127.00	126.00	ng/l
Perfluordekansyre (PFDA)	87.00	123.00	116.00	123.00	119.00	ng/l
Perfluorheksansulfonat (PFHxS)	1720.00	1640.00	689.00	322.00	200.00	ng/l
Perfluorheksansyre (PFHxA)	9170.00	1380.00	244.00	145.00	119.00	ng/l
Perfluorheptansyre (PFHpA)	2400.00	849.00	187.00	79.00	60.00	ng/l
Perfluornonansyre (PFNA)	213.00	333.00	318.00	370.00	344.00	ng/l
Perfluoroktansyre (PFOA)	1770.00	2010.00	1090.00	554.00	308.00	ng/l
Perfluoroktylsulfonat (PFOS)	18800.00	28200.00	24900.00	27000.00	25300.00	ng/l
Perfluorpentansyre (PFPeA)	13600.00	1300.00	144.00	77.00	57.00	ng/l
Sum PFC forbindelser eksl. LOQ	94100.00	75700.00	42700.00	34900.00	30200.00	ng/l
Sum PFC forbindelser inkl. LOQ	94100.00	75800.00	42800.00	35000.00	30200.00	ng/l

Table 44: Dissolved organic carbon (DOC), element concentrations, anions and PFC concentrations in water at each sampled L/S ratio of column KSU-A.

K.sund A	L/S 2	L/S 4	L/S 6	Units
Date of sampling	2012-10-18	2012-10-29	2012-11-12	
Time of sampling	9:29 AM	7:34 AM	7:38 AM	
Weight of water (g)	1133	1192	1317	g
Diff from estimated L/S ratio 2	-1	58	183	g
Temperature	14.4	14.3	11.4	°C
pH	6.52	7.1	7.46	

Conductivity (us/cm)	231	136.1	90.3	µs/cm
Klorid (Cl)	22.00	8.50	5.20	mg/l
Sulfat (SO4)	35.00	4.40	<0.25	mg/l
Fosfat (PO4-P)	8.60	32.00	61.00	µg/l
Nitrat (NO3-N)	280.00	<5	<5	µg/l
Løst organisk karbon (DOC)	67.00	55.00	48.00	mg/l
Bly (Pb), filtrert ICP-MS	0.85	4.10	1.20	µg/l
Kadmium (Cd), filtrert ICP-MS	0.04	0.03	0.02	µg/l
Kobber (Cu), filtrert ICP-MS	8.10	11.00	8.80	µg/l
Krom (Cr), filtrert ICP-MS	1.50	1.40	1.40	µg/l
Kvikksølv (Hg), filtrert	<0.002	0.06	0.13	µg/l
Nikkel (Ni), filtrert ICP-MS	4.00	2.80	2.60	µg/l
Sink (Zn), filtrert ICP-MS	160.00	180.00	200.00	µg/l
Aluminium (Al), filtrert	920.00	1000.00	1200.00	µg/l
Jern (Fe), filtrert ICP-MS	310.00	300.00	300.00	µg/l
Kalium (K), filtrert	7.10	4.70	3.60	mg/l
Kalsium (Ca), filtrert	1.40	0.80	0.63	mg/l
Magnesium (Mg), filtrert	1.20	0.30	0.16	mg/l
Mangan (Mn), filtrert ICP-MS	39.00	17.00	12.00	µg/l
Natrium (Na), filtrert	15.00	11.00	7.10	mg/l
Silisium (Si), filtrert	18000.00	6700.00	3200.00	µg/l
Arsen (As), filtrert ICP-MS	1.20	1.50	1.50	µg/l
6:2 FTS (C8)	< 75	< 75	< 75	ng/l
8:2 FTS (C10)	< 100	< 100	< 100	ng/l
PFBS (C4)	5120.00	2070.00	877.00	ng/l
PFBA (C4)	1260.00	484.00	247.00	ng/l
PFDA (C10)	< 50	< 50	< 50	ng/l
PFHxS (C6)	15900.00	16100.00	11100.00	ng/l
PFHxA (C6)	7360.00	3360.00	1590.00	ng/l
PFHpA (C7)	1400.00	855.00	500.00	ng/l
PFNA (C9)	3930.00	9160.00	10500.00	ng/l
PFOA (C8)	1880.00	2220.00	1680.00	ng/l
PFOS (C8)	542.00	1800.00	2640.00	ng/l
PFPeA (C5)	1880.00	679.00	294.00	ng/l
Sum PFC exsl. LOQ	39300.00	36800.00	29500.00	ng/l
Sum PFC incl. LOQ	39600.00	37000.00	29700.00	ng/l

Table 45: Dissolved organic carbon (DOC), element concentrations, anions and PFC concentrations in water at each sampled L/S ratio of column KSU-B.

K.sund B	L/S 2	L/S 4	L/S 6	Units
Date of sampling	2012-10-19	2012-11-02	2012-11-14	
Time of sampling	12:30 PM	12:49 PM	12:47 PM	
Weight of water (g)	1131	1119	523	g
Diff from estimated L/S ratio 2	78	66	-530	g
Temperature	12.3	13.7	13.2	°C
pH	7.46	7.64	7.95	
Conductivity (us/cm)	229	179.3	167.5	µs/cm
Klorid (Cl)	22.00	9.90	6.90	mg/l
Sulfat (SO4)	<0.25	<0.25	<0.25	mg/l
Fosfat (PO4-P)	5.30	31.00	40.00	µg/l
Nitrat (NO3-N)	<5	<5	<5	µg/l
Løst organisk karbon (DOC)	56.00	41.00	42.00	mg/l
Bly (Pb), filtrert ICP-MS	0.42	2.00	1.50	µg/l
Kadmium (Cd), filtrert ICP-MS	0.01	0.02	0.03	µg/l
Kobber (Cu), filtrert ICP-MS	6.80	5.60	5.90	µg/l
Krom (Cr), filtrert ICP-MS	1.60	1.20	11.00	µg/l
Kvikksølv (Hg), filtrert	<0.002	<0.002	<0.002	µg/l
Nikkel (Ni), filtrert ICP-MS	3.90	2.90	3.60	µg/l
Sink (Zn), filtrert ICP-MS	54.00	22.00	20.00	µg/l
Aluminium (Al), filtrert	670.00	590.00	610.00	µg/l
Jern (Fe), filtrert ICP-MS	800.00	1100.00	1000.00	µg/l
Kalium (K), filtrert	9.20	8.10	8.50	mg/l
Kalsium (Ca), filtrert	2.00	1.50	1.30	mg/l
Magnesium (Mg), filtrert	1.70	1.20	1.10	mg/l
Mangan (Mn), filtrert ICP-MS	42.00	30.00	27.00	µg/l
Natrium (Na), filtrert	16.00	12.00	11.00	mg/l
Silisium (Si), filtrert	18000.00	8600.00	6300.00	µg/l
Arsen (As), filtrert ICP-MS	0.38	0.27	0.30	µg/l
6:2 FTS (C8)	< 75	< 75	< 75	ng/l
8:2 FTS (C10)	< 100	< 100	< 100	ng/l
PFBS (C4)	4250.00	2430.00	1770.00	ng/l
PFBA (C4)	1060.00	527.00	331.00	ng/l
PFDA (C10)	< 50	< 50	< 50	ng/l
PFHxS (C6)	11800.00	12400.00	13300.00	ng/l
PFHxA (C6)	6490.00	3840.00	2800.00	ng/l
PFHpA (C7)	1260.00	907.00	779.00	ng/l
PFNA (C9)	3140.00	4930.00	5620.00	ng/l
PFOA (C8)	1360.00	1530.00	1680.00	ng/l
PFOS (C8)	807.00	2020.00	2780.00	ng/l

PFPeA (C5)	1850.00	944.00	633.00	ng/l
Sum PFC exsl. LOQ	32000.00	29600.00	29700.00	ng/l
Sum PFC incl. LOQ	32200.00	29800.00	29900.00	ng/l

10.3.2 Supplementary figures for the concentration of PFCs in leachate over time

The figures in this section are meant supplement the figures from column experiments with soil from Bergen and Kristiansund using average concentrations in the section 5.3 Column experiments (results). Columns from Bergen had very little difference between parallel columns, while Kristiansund had slightly higher difference between parallel columns. ***Figure 77*** and ***Figure 78*** show the concentration of PFCs in leachate of the individual columns from Bergen over time. ***Figure 79*** and ***Figure 80*** show the concentration of PFCs in leachate of the individual columns from Kristiansund over time.

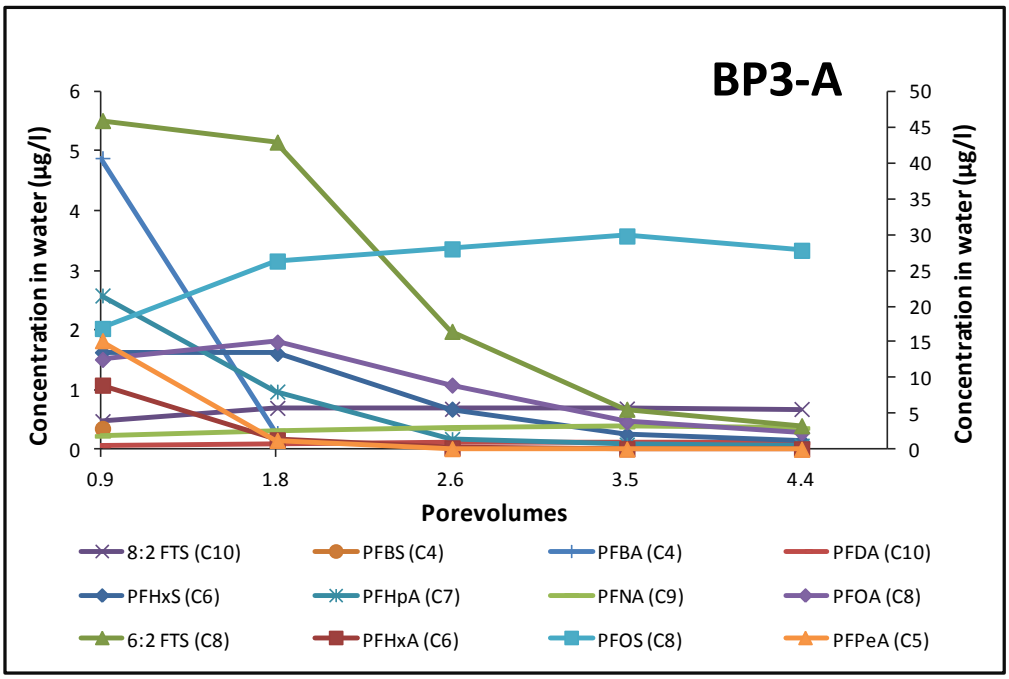

Figure 77: Concentrations of PFCs (µg/l) over time in effluent water from the column BP3-A. A total of 4.4 porevolumes of water was flushed through the soil column during the 35 days of the experiment. The compounds PFOS, 6:2 FTS, PFPeA and PFHxA are shown using a secondary axis.

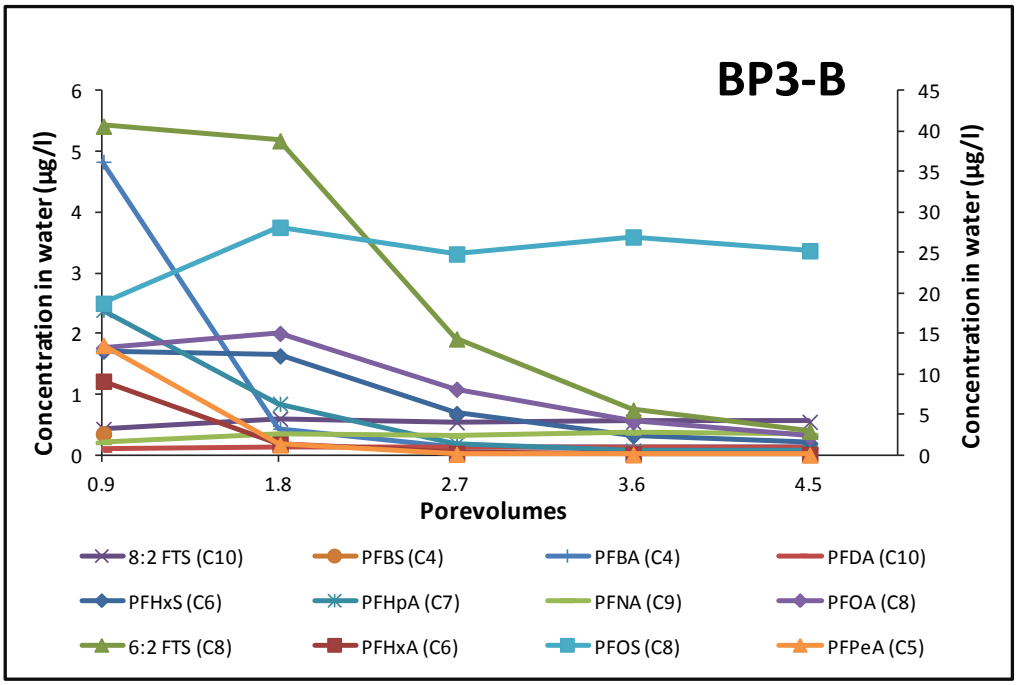

Figure 78: Concentrations of PFCs (µg/l) over time in effluent water from the column BP3-B. A total of 4.5 porevolumes of water was flushed through the soil column during the 35 days of the experiment. The compounds PFOS, 6:2 FTS, PFPeA and PFHxA are shown using a secondary axis.

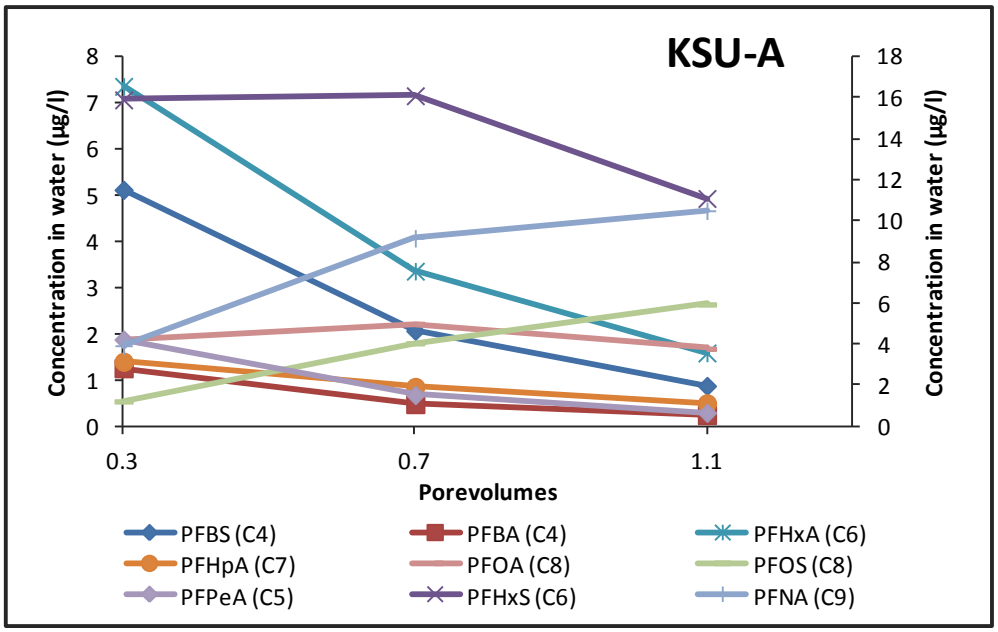

Figure 79: Concentrations of PFCs (µg/l) over time in effluent water from the column KSU-A. A total of 1.1 porevolumes of water was flushed through the soil column during the 35 days of the experiment. The compounds PFHxS and PFNA are shown using a secondary axis.

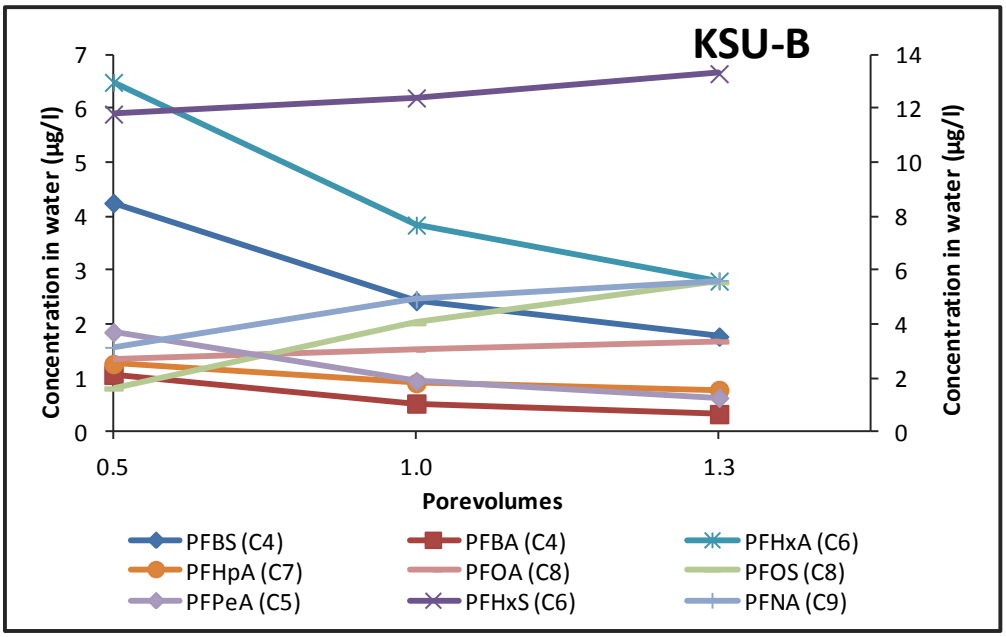

Figure 80: Concentrations of PFCs (µg/l) over time in effluent water from the column KSU-B. A total of 1.3 porevolumes of water was flushed through the soil column during the 35 days of the experiment. The compounds PFHxS and PFNA are shown using a secondary axis.

10.3.3 Supplementary figures for the accumulated amount of PFCs leached out of soil over time

Figure 81 and ***Figure 82*** show the accumulated amount of PFCs in leachate of the individual columns from Bergen over time. ***Figure 83*** and ***Figure 84*** show the accumulated amount of PFCs in leachate of the individual columns from Kristiansund over time.

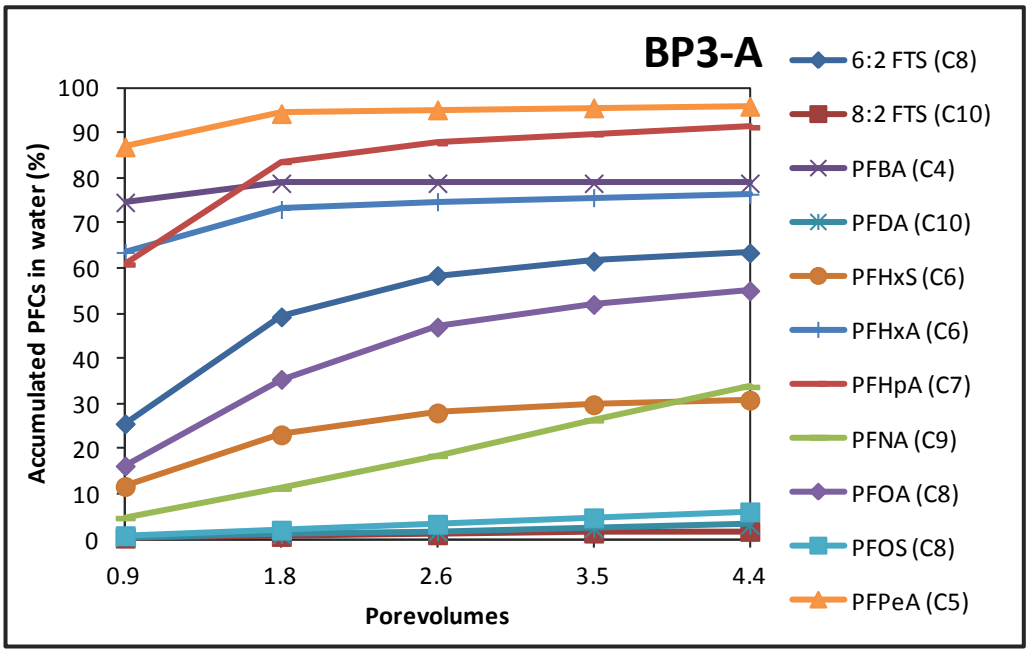

Figure 81: Accumulated PFCs (%) with time in the effluent water of column BP3-A.

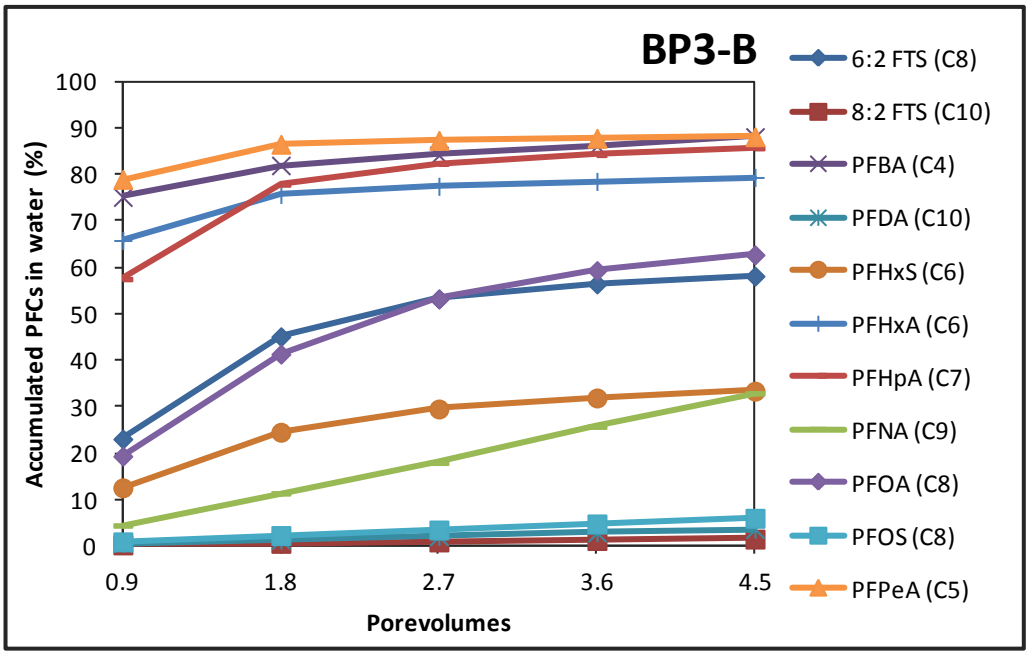

Figure 82: Accumulated PFCs (%) with time in the effluent water of column BP3-B.

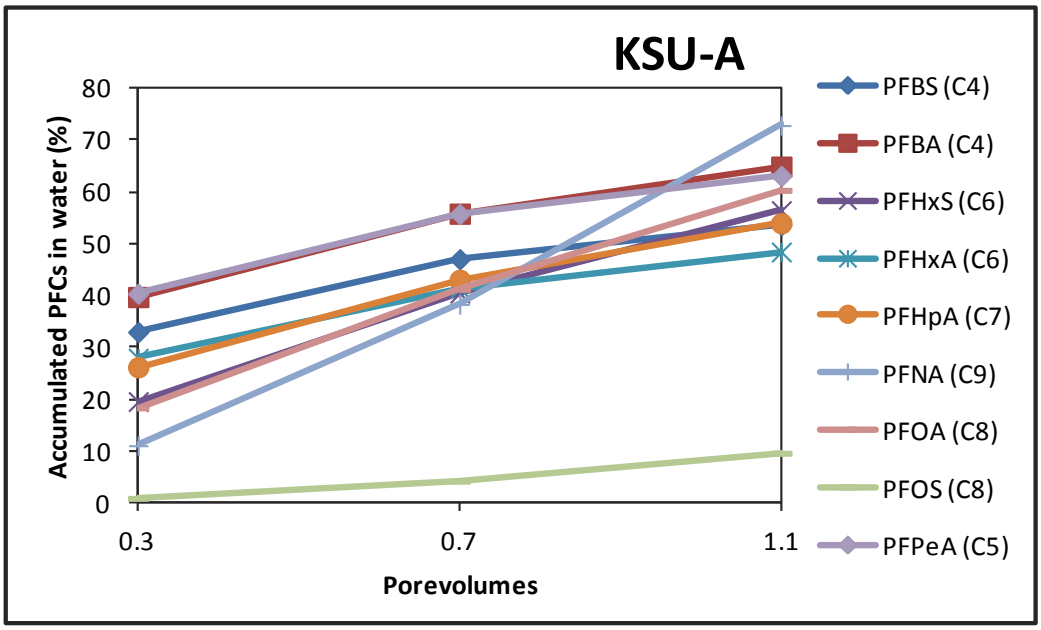

Figure 83: Accumulated PFCs (%) with time in the effluent water of column KSU-A.

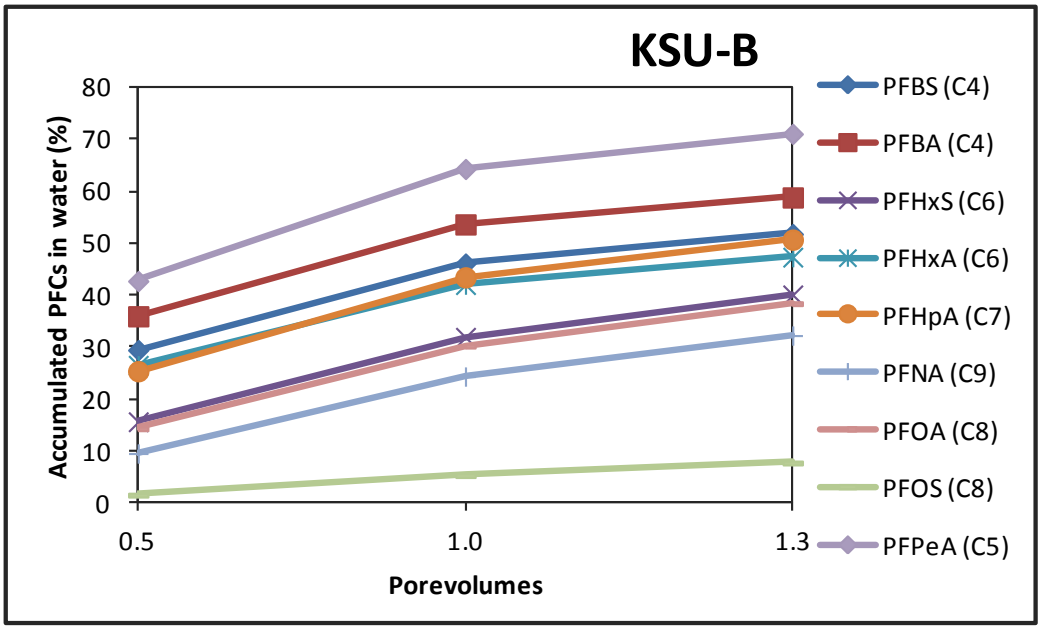

Figure 84: Accumulated PFCs (%) with time in the effluent water of column KSU-B.